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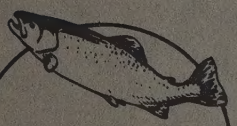
ZOOPLANKTON ABUNDANCE IN HAWAIIAN WATERS, 1953-54



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FISH AND WILDLIFE SERVICE

Explanatory Note

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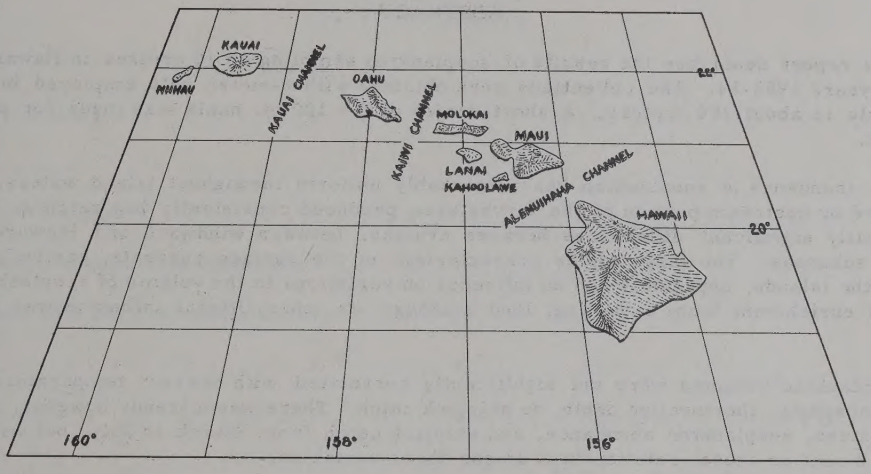

ZOOPLANKTON ABUNDANCE IN HAWAIIAN WATERS, 1953-54

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ABSTRACT

This report describes the results of zooplankton sampling on 10 cruises in Hawaiian waters during the years 1953-54. The collections were obtained with 1-meter nets employed in 30-minute oblique hauls to about 200 meters. A short series of 0 - 100 m. hauls was made for purposes of comparison.

The abundance of zooplankton was remarkably uniform throughout island waters. Although the eastward or upstream portion of the survey area produced consistently low catches, there were no statistically significant differences between cruises, between windward and leeward areas or among six subareas. The large eddies characteristic of the surface currents, particularly to the leeward of the islands, apparently had no influence on variations in the volume of zooplankton. Also, evidence of enrichment from upwelling, land drainage, or other littoral influence was obscure or lacking.

Zooplankton volumes were not significantly correlated with water temperature, salinity, inorganic phosphate, thermocline depth, or skipjack catch. There was a trend, however, of increasing temperature, zooplankton abundance, and skipjack catch from March to July, but we doubt that there were direct or causal relationships among these variables.

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In conjunction with researches on the tuna resources of the Hawaiian offshore waters, the Pacific Oceanic Fishery Investigations (POFI) has studied the geographical and seasonal variations in zooplankton abundance. Tuna presence and abundance may be dependent to a great extent upon food supply, and zooplankton is directly or indirectly an important food source for these large, oceanic fishes (Reintjes and King 1953, King and Ikehara 1956).

During the years 1950 to 1954 plankton sampling was conducted on 17 POFI cruises in Hawaiian waters. An earlier report (King and Hida 1954) presented an analysis of collections obtained on 7 cruises in 1950-52. The present report is concerned with collections from 10 cruises in 1953-54. In addition to zooplankton sampling, on all cruises a number of observations and measurements were made of the chemical and physical environment. For example, two of the cruises included oceanographic observations to 500 - 1,200 meters depth, with temperature, salinity, and phosphate measured at each depth sampled. Bathythermograph observations were made routinely on all cruises. The results of the oceanographic observations have appeared in previous publications (McGary 1955, Seckel 1955).

The primary purpose of this report is to present the results of the plankton sampling, information which is applicable to the study of the abundance and distribution of skipjack, Katsuwonus pelamis (Linnaeus), in Hawaiian waters. The skipjack catch is characterized by a marked seasonal variation and is also subject to annual fluctuations which are as yet unexplained. In the years 1950 and 1951, zooplankton samples collected in midsummer during the height of the skipjack season were about 20 percent larger in volume than those taken in late summer and fall after the close of the season (King and Hida 1954). This difference in relative food abundance may have had no direct influence, however, on skipjack presence and distribution.

One hypothesis seeming worthy of further testing was that areas to the lee of the island chain might be higher in zooplankton abundance than areas to windward because of the possible enrichment from the littoral waters of the islands and from the upwelling which may theoretically occur in the lee of oceanic islands. As the Hawaiian archipelago extends generally in a southeast-northwest direction, and since the prevailing tradewinds are from the northeast and the major ocean currents from the east and northeast, a line was drawn (King and Hida 1954) connecting the various islands of the group and thus dividing the island waters into windward and leeward areas. In order to examine statistically differences between, and within, these major areas, they were subdivided into 6 subareas, 3 leeward and 3 windward of the islands.

Although the abundance of zooplankton was again found to be remarkably uniform, geographically, throughout the Hawaiian area, the easterly region adjacent to, and upstream from, the island of Hawaii consistently yielded the lowest volumes. With the benefit of recent analyses of the physical environment (McGary 1955, Seckel 1955) we can now better understand the general uniformity in the plankton and also the causes for small but possibly significant variations.

SOURCE OF MATERIAL

This study is based primarily on 215 quantitative zooplankton collections obtained on 6 cruises of M/V Hugh M. Smith and 4 cruises of M/V Charles H. Gilbert. Several of these expeditions were of short duration and consisted of repeated visits to three set locations, or stations, which were selected as being representative of plankton and hydrographic conditions on the skipjack fishing grounds. Smith

cruises 20 and 21 were of longer duration and provided synoptic observations of both insular and oceanic waters throughout the Hawaiian area. On Gilbert cruise 16, a short series of hauls was made to determine the difference in catch of zooplankton and tuna larvae in 0- to 100-meter and in 0- to 200-meter tows during day and night hours.

The approximate locations of the plankton stations are shown in figures 1 to 4. More exact positions together with date and hour of hauling, amount of water strained, and the zooplankton volumes for each station are given in the Appendix, tables 6 to 11. Data collected on earlier cruises in 1950-52 and published in a previous report (King and Hida 1954), are also utilized in this study.

METHODS

All of the collections were obtained with 1-meter (mouth diameter) nets of 30XXX silk grit gauze (apertures averaging 0.65 mm. in width), equipped with flowmeters. Oblique hauls of approximately 30 minutes' duration to a depth of about 200 meters were employed at most stations. At station C, one of the "permanent" stations visited on a number of cruises, hauls were made to 40 or 50 meters because of the shallow depth of water (50 to 100 meters); on Gilbert cruise 16 a short series of oblique hauls was made to 100 meters depth. A more complete description of the net used and of the method of hauling plus the calculation of sampling depth and amount of water strained have been provided in an earlier report (King and Demond 1953).

The method of processing the samples in the laboratory was essentially as employed by King and Hida (1954). Following the usual procedure at the POFI laboratory, the volume of all organisms less than 2 cm. in length plus the volume of organisms 2 to 5 cm. in length that might be considered of significant nutritional value, were combined to give a single volume measurement for each sample. This figure was divided by the estimated amount of water passing through the net, as determined from the flowmeter reading, to obtain the volume of zooplankton, as food, per unit of water strained.

The volumes from all standard hauls were adjusted to remove the effects of diurnal variation by the method described by King and Hida (1954). Briefly, this consists of calculating the regression of plankton volume on solar time of day, the latter expressed as a sine function. The zooplankton volumes are increased or reduced dependent upon the hour of hauling and adjusted to 0600 or 1800 hours when the corresponding sine value is 0. Solar time is presently used in the calculations. The method provides a reasonably good correction for day-night differences as judged by the significance of the "t" values and the night/day ratios for the adjusted volumes (table 1).

The data from the 7 cruises listed in table 1 were adjusted by individual cruise. A pooled regression coefficient ($b = 0.1110$) calculated from the combined data of these 7 cruises, most of which provided rather thorough coverage of the Hawaiian area and during which stations were visited consecutively regardless of time of day or night, was used in adjusting the few volumes of cruises 11, 12, 13, and 16 of the Gilbert and cruises 22, 23, 24, and 26 of the Smith. On these latter cruises sampling was not conducted around the clock, or there were too few data to be adjusted by individual cruise. Throughout this report we have employed the adjusted volumes, except when noted for shallow hauls.

VARIATION WITH DEPTH

A short series of experimental hauls made on Gilbert cruise 16 provided an opportunity to compare the difference between the standard, 200-meter, oblique haul and a 100-meter, oblique haul in the catch of zooplankton during both day and night periods. A special effort was made to obtain an accurate count of the tuna larvae and other fish larvae in these samples. The results, summarized in table 2, demonstrate the superiority of night over day and of shallow over deeper hauls in the capture of zooplankton, tuna larvae, and other fish larvae. Disregarding depth of hauling, the night samples averaged 2.5 times as great in bulk as the day samples. In respect to depth, disregarding time of hauling, the 100-meter hauls averaged 1.6 times as great as the deeper 200-meter hauls.

Although the data are very limited they provide some other interesting conclusions. For zooplankton as a whole the difference in catch rate between 0- to 100- and 0- to 200-meter hauls is slightly less in the daytime than at night, resulting, we believe, from a downward migration and general dispersal of the plankton throughout the upper layers during the day, and its greater concentration near the surface at night. The tuna and other fish larvae were generally more abundant near the surface at both times, but the vertical differences in their distribution were not quite as great at night as in the day. Also in respect to the fish larvae, there was a higher night/day ratio for the 200-meter hauls than for the 100-meter hauls. Both

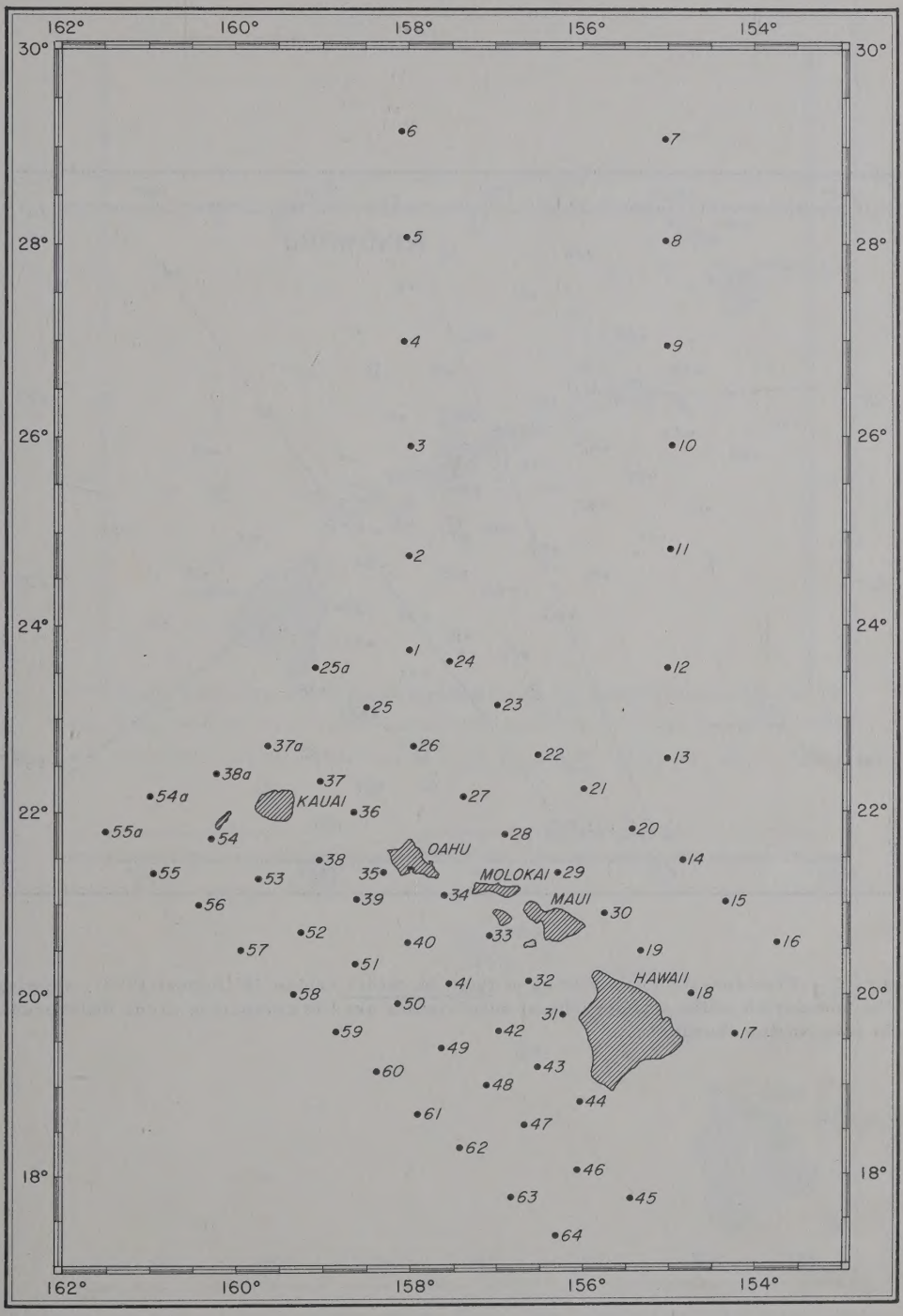

Figure 1.--Plankton-station positions of Hugh M. Smith cruise 20 (February - April 1953).

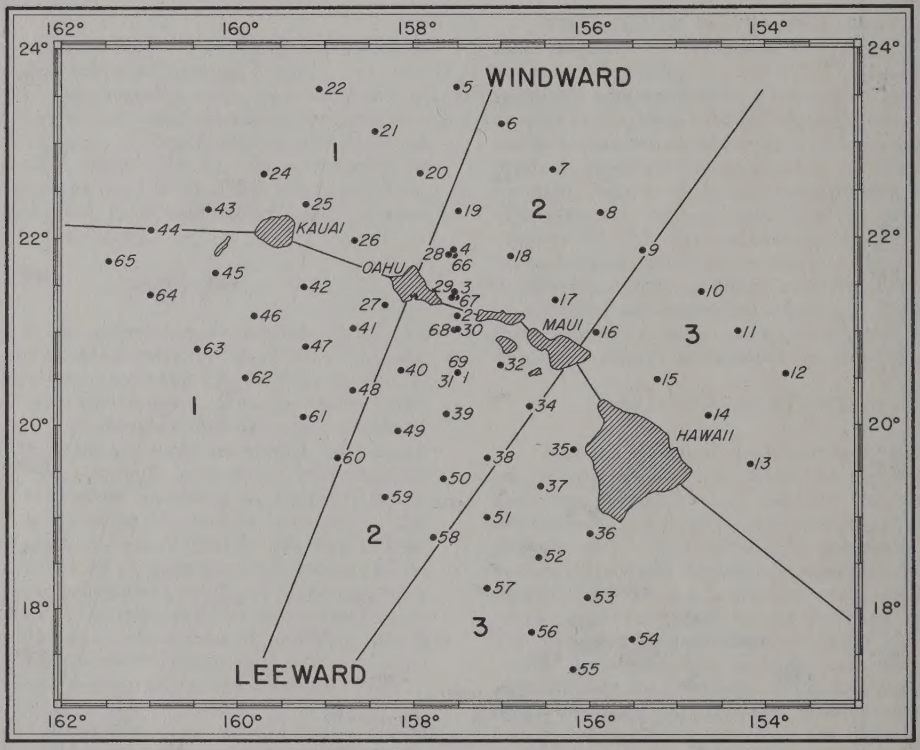

Figure 2.--Plankton-station positions of Hugh M. Smith cruise 21 (August 1953), showing the boundaries of the 6 geographical subdivisions used in comparing areal differences in zooplankton abundance.

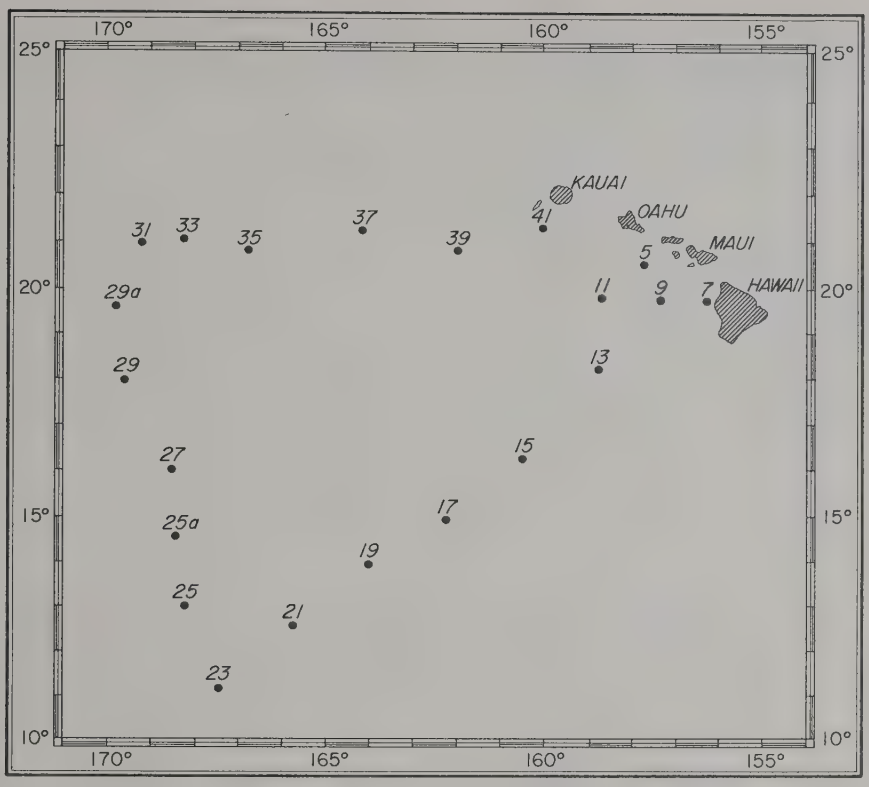

Figure 3.--Plankton-station positions of Hugh M. Smith cruise 26 (May - June 1954).

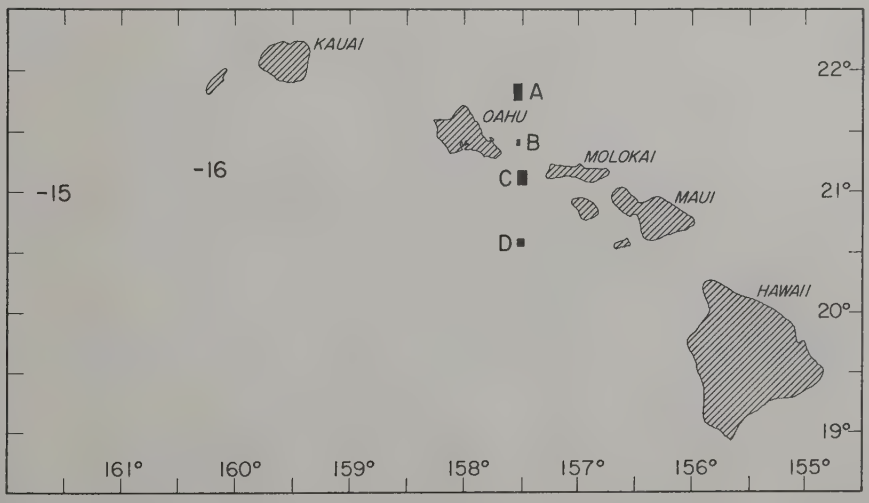

Figure 4.--General locality of stations A, B, C, and D visited repeatedly on Charles H. Gilbert cruises 11, 12, and 13 (April - June 1953), and Hugh M. Smith cruises 21, 22, 23, and 24 (August - December 1953); plankton hauls were made at station B only on Hugh M. Smith cruise 21. Also shown are positions (-) of plankton stations 15 and 16 of Charles H. Gilbert cruise 16 (August 1954).

Table 1.--Comparison of the means and night/day ratios of unadjusted and adjusted volumes, also the regression coefficients (b), "t" values, and probability values for the sine transformation method of adjustment for 7 cruises in Hawaiian waters

Vessel and cruise	Period	Mean volume		Night/day ratio		b	t	Degrees of freedom	P
		Unadjusted	Adjusted	Unadjusted	Adjusted				
Hugh M. Smith-10	July 1951	26.0	25.6	1.39	0.97	0.1128	2.945	32	< 0.01
John R. Manning-8	Sept.-Oct. 1951	22.2	21.2	1.70	1.03	0.1488	8.313	34	< 0.001
Hugh M. Smith-12	Oct.-Nov. 1951	20.2	20.3	1.57	1.04	0.1231	4.076	28	< 0.001
John R. Manning-9	Nov. 1951	27.0	26.5	1.30	1.00	0.0688	5.375	30	< 0.001
Hugh M. Smith-17	Sept. 1952	26.5	26.4	1.47	1.05	0.1033	4.943	28	< 0.001
Hugh M. Smith-20	Feb.-Apr. 1953	16.5	16.2	1.44	1.07	0.0884	5.632	67	< 0.001
Hugh M. Smith-21	Aug. 1953	16.4	16.0	1.55	1.04	0.1238	6.732	62	< 0.001
Average		22.1	21.7	1.49	1.03	0.1099			

Table 2.--Variation in volume of zooplankton and in numbers of fish larvae with depth of hauling, Charles H. Gilbert cruise 16

Station	Time	Sample	Approx. depth, m.	Zooplankton volume, cc./1000m.^{3}	Fish larvae number/1000m.^{3}	
					Tuna	Total
15	Night	1	200	43.7	6.0	121.4
	(2121-	2	100	56.1	7.5	116.5
	2336)	3	200	32.3	2.9	96.6
		4	100	69.4	15.2	235.1
16	Day	1	200	17.2	0	54.6
	(0926-	2	100	24.4	2.2	85.5
	1138)	3	200	15.8	1.3	34.8
		4	100	24.6	1.6	106.0
15	Night	Mean	200	38.0	4.4	109.0
	"	"	100	62.8	11.4	175.8
16	Day	"	200	16.5	0.6	44.7
	"	"	100	24.5	1.9	95.8
15	Night	Mean	Depths	50.4	7.9	142.4
16	Day	"	combined	20.5	1.3	70.2
Stations	Times	Mean	200	27.2	2.5	76.8
combined	combined	"	100	43.6	6.6	135.8
Ratios						
15	Night		100/200	1.65	2.59	1.61
16	Day		100/200	1.48	3.17	2.14
15/16	Night/Day		200	2.30	7.33	2.44
	"		100	2.56	6.00	1.84

of these conditions are just the reverse of that found for the zooplankton as a whole.

GEOGRAPHICAL AND TEMPORAL VARIATIONS

Oceanographic observations have shown that Hawaiian waters provide a comparatively homogeneous environment both in time and space in respect to surface temperature, salinity, and inorganic phosphate. The surface current pattern, however, is of complex nature (fig. 5) and is characterized, particularly to the leeward of the islands, by large cyclonic or anticyclonic vortices (McGary 1955, Seckel 1955). A comparison of sigma-t and inorganic phosphate cross-sections has indicated that enrichment of the surface layers through lateral mixing associated with these eddies is insignificant (McGary 1955). There are, therefore, no a priori reasons to expect large variations in plankton abundance either geographically or seasonally. The relatively slight but consistent variations that do occur are noteworthy, however.

In figure 6 we have attempted to show areas of similar zooplankton concentration for the two cruises of the Smith which employed oblique hauls to 200 meters depth and afforded general coverage of the area. Although the results indicate conditions of remarkable uniformity throughout the island waters, there were certain localities which, in agreement with past sampling, were generally richer or poorer than other areas. For example, stations southwest of Oahu produced volumes higher than average, and the eastern portion of the survey area again produced consistently low catches. The area north to northeast of Kauai, which was considerably above average on two earlier cruises (King and Hida 1954), yielded only one unusually large sample.

From an analysis of variance of completely randomized design, employing the zooplankton volumes from cruises 20 and 21, we conclude that there were no statistically significant differences ($P > 0.05$) between cruises, between windward and leeward areas, or among the 6 subareas with boundaries as shown in figure 2. In an analysis of earlier data we found significant differences ($P < 0.05$) among cruises but no significant differences among areas or subareas (King and Hida 1954). Despite the lack of statistically significant differences among subdivisions of the region, the repeated occurrence of low catches to the east or just upstream of the

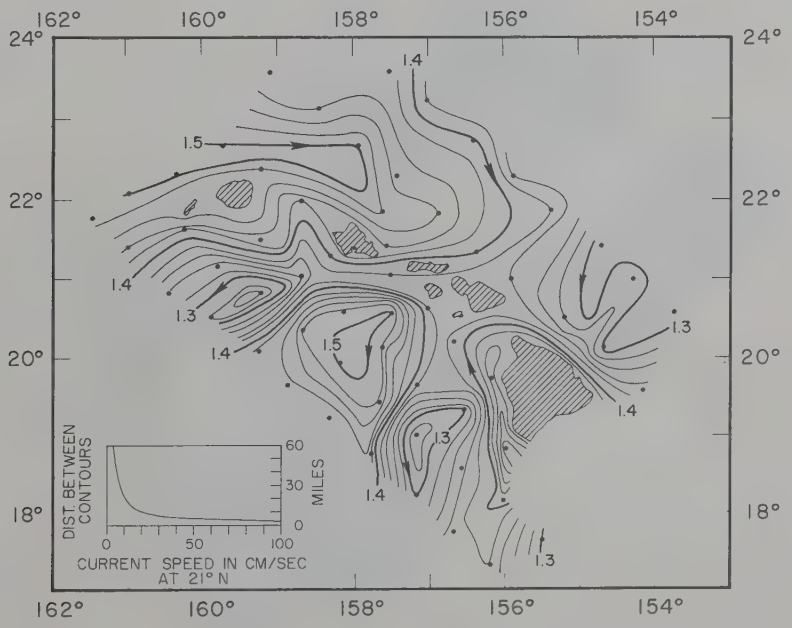

Figure 5.--Dynamic height anomalies (dynamic meters) at the surface relative to 500 m., Hugh M. Smith cruise 21, August 1953. Contour interval 0.02 dynamic meters. [From Seckel 1955, fig. 29]

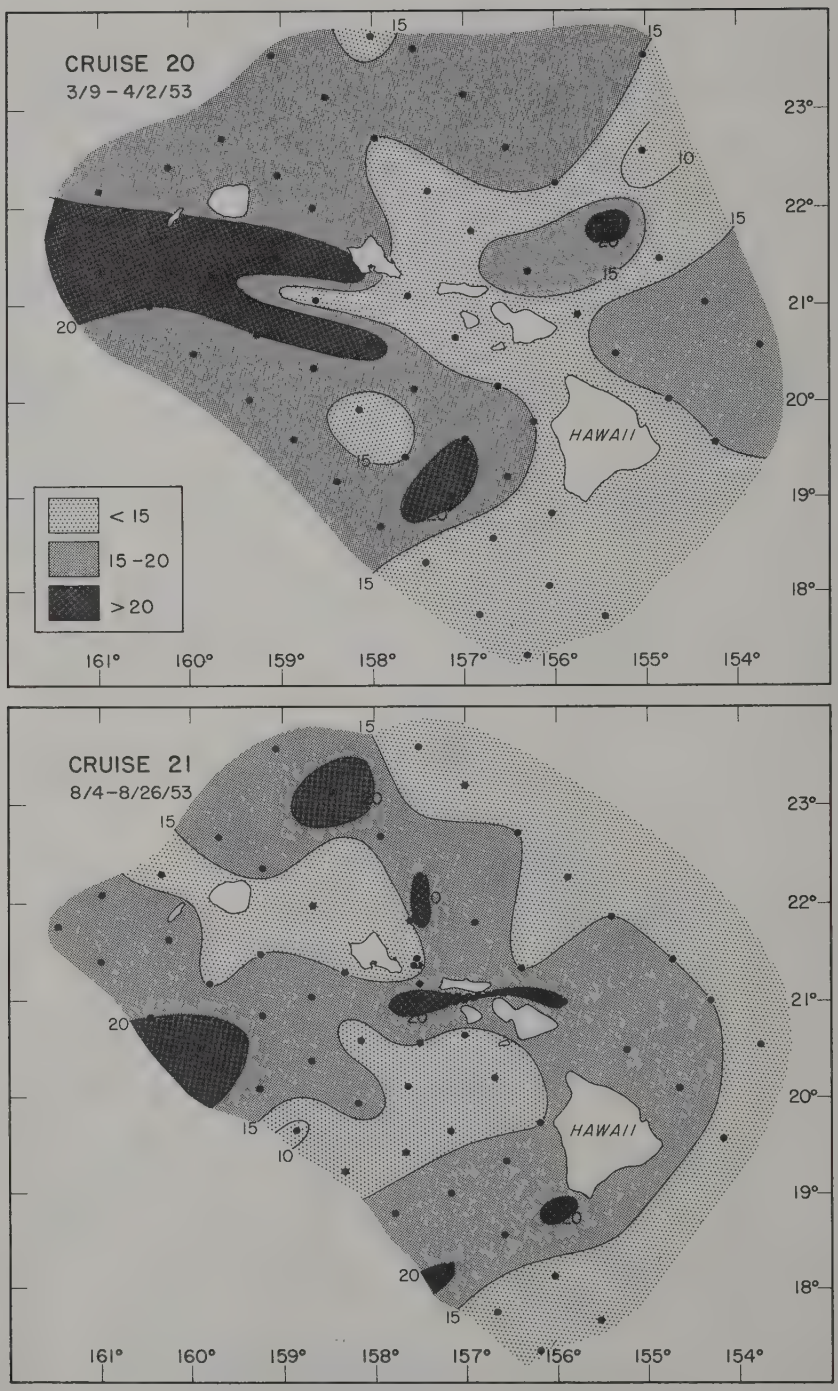

Figure 6.--Variations in zooplankton abundance, based on time-adjusted volumes as cc./1000 $m.^3$, for two cruises of the Hugh M. Smith.

island chain would seem to have definite ecological significance.

McGary (1955) pointed out that, on Smith cruises 10 and 12, zooplankton maxima were associated with the cyclonic eddies in the lee of the islands, and concluded that "the occurrence of the zooplankton maxima at or near the centers of the cyclonic eddies and the frequent occurrence of high salinities and low temperatures at their centers are the result of divergent motion which causes some enrichment of the surface water. The slightness of the maxima and the number of exceptions to the increase of salinity and decrease of temperature at the centers indicate that vertical motion is small and intermittent at best."

One method, perhaps, of testing for signs of occasional enrichment resulting from the eddies is to compare the standard deviation of the means of zooplankton volumes obtained from areas with eddies (i.e. areas in which the eddies are centered) with the standard deviation from areas without eddies. If the occasional occurrence of unusually large volumes were particularly associated with the eddy systems (as defined and located by McGary 1955 and Seckel 1955), then the means from these areas might be expected to have a high variance. In table 3 we show the means and standard deviations for 5 cruises of the Smith which provided comprehensive coverage of Hawaiian waters. There is no evidence supporting the assumption as stated above. In fact, the average standard deviation (5.2) for areas without eddies was larger than for areas with eddies (4.8), but the difference was not great.

According to Seckel (1955), on cruises 17 and 21 conducted during late summer months under conditions of normal tradewind weather, the greatest extremes in surface temperature occurred on the leeward side of the island chain; on cruise 21 the surface inorganic phosphate averaged 0.2 μg at./L. for the windward side and 0.3 μg at./L. on the leeward side. In respect to the zooplankton, on these two cruises the highest variability and the highest average volumes were obtained on the windward side (table 3); the differences between windward and leeward areas are statistically not significant, however. It is of interest that on cruise 20, conducted during a late winter month (March) and also under tradewind conditions, the highest variability and highest average volume were obtained on the leeward side; again the differences were not statistically significant. It is possible, therefore, that the differences shown in table 3 for five cruises providing comprehensive coverage of the Hawaiian area are the result of chance variation; they supply no conclusive evidence of enrichment downstream from the islands as the result of eddy systems, upwelling, land drainage, or other influence of the littoral waters.

Although we have collected a rather large number of plankton samples in Hawaiian waters during the years 1950 - 1954, they are not adequate to describe seasonal variations or differences among years. In figure 7 we show the mean volumes obtained on all cruises employing a uniform sampling method (i.e. oblique hauls to 200 meters depth with 1-meter nets of 30XXX grit gauze). Some of the cruises gave compresive coverage of the Hawaiian area, whereas

Table 3.--Comparison of mean zooplankton volume ($\bar{x}$), as cc./1000 $m.^3$, and standard deviation (s) of the mean, for 6 subareas of the windward and leeward Hawaiian waters, sampled on 5 cruises of the Hugh M. Smith. An asterisk indicates the presence (center) of an eddy in the subarea at time of sampling

Cruise	Period		Windward				Leeward				Cruise average
			1	2	3	Area average	1	2	3	Area average	
10	7/21-30/51	$\bar{x}$	36.5	26.0	22.8	27.4	26.8	21.4	24.2	24.0	25.6
		s	17.3	4.6	9.6	11.3	7.9	10.7*	9.0*	9.1	10.2
12	10/24-11/1/51	$\bar{x}$	22.6	16.9	15.1	18.1	28.6	19.3	19.1	21.9	20.3
		s	3.1	2.7	2.1	4.0	5.8*	2.9	4.7*	6.0	5.5
17	9/6-14/52	$\bar{x}$	27.4	29.9	24.1	26.9	27.6	27.8	23.2	25.8	26.4
		s	3.2	9.5	4.0	6.2	3.4	4.0*	3.0	4.0	5.2
20	3/9-4/2/53	$\bar{x}$	16.8	15.4	15.5	16.0	19.4	16.1	16.9	16.9	16.2
		s	1.6*	3.8*	2.3	2.5	3.6*	3.0*	3.6	3.9	3.4
21	8/4-26/53	$\bar{x}$	17.8	16.0	15.8	16.4	17.0	15.1	16.4	16.1	16.2
		s	8.4	3.2	2.7	5.0	3.3*	4.0*	4.0*	3.8	4.3

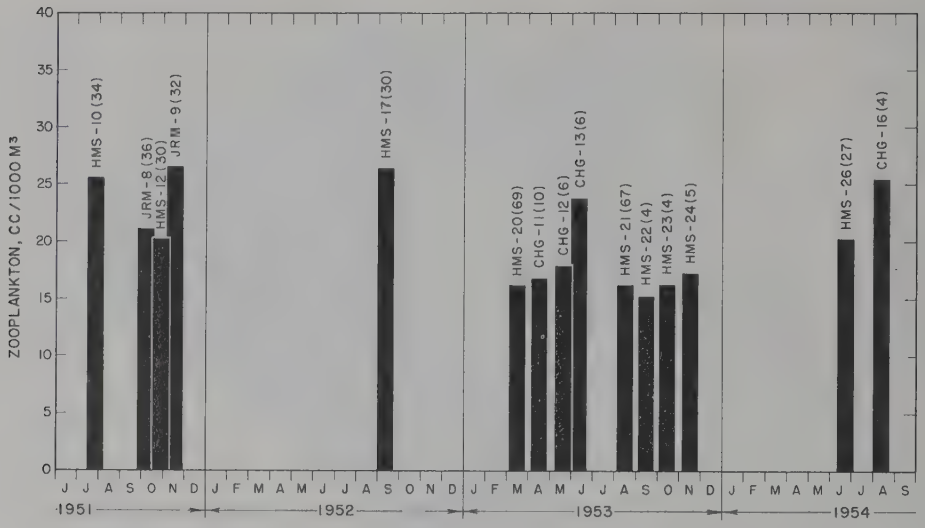

Figure 7.--Mean zooplankton volumes by cruise for each month of sampling during the period July 1951 - August 1954. Number of samples is shown in parentheses.

others were greatly limited in scope, but the localities sampled were thought to be representative of the region. Perhaps the most outstanding feature of the data is the uniformly low average volumes obtained in 1953. Sampling conducted during 8 months of that year revealed a persistent low level of plankton abundance, broken only in the month of June.

Although our sampling was also inadequate for a seasonal comparison, when data for like months are combined the results (fig. 8) show a trend of increasing zooplankton abundance from March to July. Following July, the average volumes became quite variable. Unfortunately we have no plankton data for the months of January, February, and December.

In his study of the chemical and physical properties of Hawaiian waters, Seckel (1955) stated that he could discern no definite seasonal cycle in temperature or salinity as observed on one winter and two summer cruises. The seasonal range in temperature was about 4°F. which was less than the range which might be encountered on any one cruise as the result of geographical variations. So it is perhaps not surprising that we found no marked seasonal variation in zooplankton abundance.

As judged by the catch of the Hawaiian pole-and-line fishery (Yamashita 1957), the abundance of skipjack varies greatly with season, the bulk of the catch, on the average, being obtained during the months of June, July, and August (fig. 8). Although we obtained the highest average volume of zooplankton in July that month was sampled in only one year; moreover, the differences between months throughout the year were slight as compared with the wide variation in fish catch. Although there is a rough seasonal correspondence between zooplankton abundance and water temperature (fig. 8), we must conclude that, when our data are summarized as in figure 8, there is little evidence of any causal relationship or close covariation between zooplankton and surface temperature or zooplankton and skipjack catch.

CORRELATIONS WITH ENVIRONMENTAL FACTORS

Despite evidence of great uniformity in both the biological and the physical and chemical environment, we thought it worthwhile to examine the degree of correlation of zooplankton catch and certain factors considered most likely to have biological significance. The results from three major cruises, summarized in table 4, show lack of significant correlation between zooplankton volumes and temperature (at 10 meters depth), surface inorganic phosphate[1/]

[1/] The temperature and phosphate data employed in these statistical tests have been published in reports of McGary (1955) and Seckel (1955).

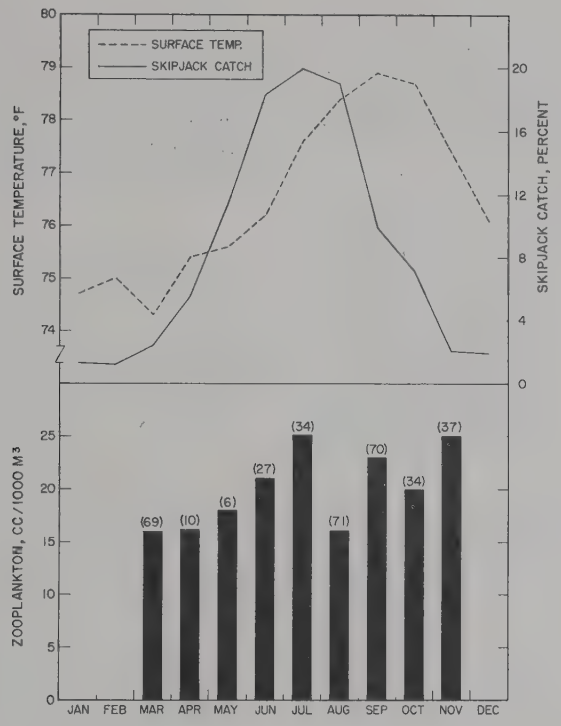

Figure 8.--Monthly variation in zooplankton abundance, surface temperature, and skipjack catch in Hawaiian waters. The zooplankton data are for the years 1951 - 1954 and were obtained on Hugh M. Smith cruises 10, 12, 17, 20, 21, 22, 23, 24, and 26; John R. Manning cruises 8 and 9; and Charles H. Gilbert cruises 11, 12, 13, and 16. Number of zooplankton samples is shown in parentheses. The temperature data constitute a 6-year average, 1950 - 1955, and were assembled by Gunter Seckel, Oceanographer, POFI. The skipjack catch data are a 4-year average, 1951 - 1954, derived from monthly catch data supplied by the Territory of Hawaii, Division of Fish and Game.

Table 4.--Results of correlation analyses comparing adjusted zooplankton volumes of Hugh M. Smith cruises 20, 21, and 26, and certain environmental factors

Cruise	X_1 variate	X_2 variate	Degrees of freedom	Correlation coefficient, r	P
20	Zooplankton volumes (cc./1000 $m.^3$)	Temperature (°C) at 10 meters depth	67	0.214	> 0.05
20	do.	Thermocline depth (meters)	67	-0.019	> 0.05
21	do.	Temperature (°C) at 10 meters depth	65	0.124	> 0.05
21	do.	Thermocline depth (meters)	65	0.032	> 0.05
21	do.	Surface inorganic phosphate (μg at./L.)	65	-0.044	> 0.05
26	do.	Temperature (°C) at 10 meters depth	19	-0.103	> 0.05
26	do.	Thermocline depth (meters)	19	0.332	> 0.05

and depth to the top of the thermocline. This lack of correlation with the fields chosen may be of significance in itself, and would seem to indicate that other, more fundamental factors of the environment may be the causative agents for the variations observed.

During the period April - December 1953, four "permanent" stations between Oahu and Molokai were visited at approximately weekly intervals with sampling of zooplankton (at three of the stations only), temperature, phosphate, and salinity, for the purpose of following detailed changes in the environment associated with the opening of the skipjack season in the early summer months and the decline in the catch during the fall. It was assumed that these selected locations would yield data fairly representative of conditions throughout Hawaiian waters.

The northernmost station, station A (fig. 4), was positioned so as to sample "open ocean" water to the windward of the islands, station B to sample channel water, station C to sample water over Penguin Bank where the depth ranged from 50 to 100 meters, and station D the open ocean to the leeward of the islands. Station A was normally visited at about 1300, station B at 1900, station C at 2300, and station D 0300 hours. At each station where depth of water permitted, samples were taken between 0 and 250 or 300 meters (500 meters on Smith cruise 21) for salinity and phosphate measurements. Surface temperatures were taken with a bucket thermometer; subsurface temperatures were recorded with a bathythermograph. Only the surface data are utilized in this report, however.

Plankton hauls were made at station B on only one cruise. The 3 samples obtained at this location on Smith cruise 21 averaged 13.2 cc./1000 $m.^3$. The 19 successful hauls made at station C on Penguin Bank, which were shallow tows between the surface and 40 or 50 meters depth, yielded an average volume of 29.3 cc./1000 $m.^3$. This mean had considerably higher variance than the means for station A (16.2 cc./1000 $m.^3$) and station D (19.4 cc./1000 $m.^3$), both the latter stations being in deep water and sampled with 0- to 200-meter oblique hauls.

When the various observations obtained at stations A and D are plotted as in figure 9, we obtain a complex and confusing picture of rapid fluctuations in the environment with no definite seasonal trends and with very little agreement between the two stations. Surface temperatures of the two localities varied in somewhat parallel manner, however, with station A being about 1°F. cooler on the average than station D. Correlation analyses based on the repeated observations made at station D, summarized in table 5, showed no significant correlations between zooplankton volume and surface temperature, surface inorganic phosphate, thermocline depth, surface salinity, and the weekly skipjack catch for the Hawaiian area.

If we replot the temperature and zooplankton data obtained at station D during the early weeks (April - June) of the survey, together with the skipjack catch for the entire Hawaiian area for the same period, we find an interesting covariation (fig. 10). Warming of the water in early April was accompanied by an increase in zooplankton and in catch of skipjack. Subsequent cooling about the middle of April was associated with a drop both in zooplankton and skipjack catch. As the temperature increased during May and June there was again a corresponding general increase in zooplankton and skipjack abundance. We are not able to define the causative factors in this sequence of events. The correlation coefficients for surface temperature and zooplankton ($r = 0.385$) and for skipjack and zooplankton ($r = 0.593$) were below the 5-percent level of significance ($r_{.05} = 0.602$). Surface temperature and skipjack, however, showed a highly significant correlation ($r = 0.777$), beyond the 1-percent level of significance ($r_{.01} = 0.735$). It is possible that none of the factors examined are directly related, but that all exhibit chance variations, or that all are governed by changes in the general circulation or some other basic, underlying condition in the environment as yet undetermined.

SUMMARY

1. In this second report of the Pacific Oceanic Fishery Investigations on variations in zooplankton abundance in Hawaiian waters, we summarize the results of plankton hauling on 10 cruises during the years 1953 - 54. Data from earlier cruises, included in a previous report (King and Hida 1954) were also utilized to some extent in drawing conclusions.

2. The collections were obtained with 1-meter nets of 30XXX grit gauze (aperture widths 0.65 mm.). Oblique hauls to about 200 meters' depth were employed at most stations. The results from a short series of 0- to 100-meter hauls are also included.

3. The displacement volumes of all samples were measured in the laboratory. For each sample there was calculated the volume of

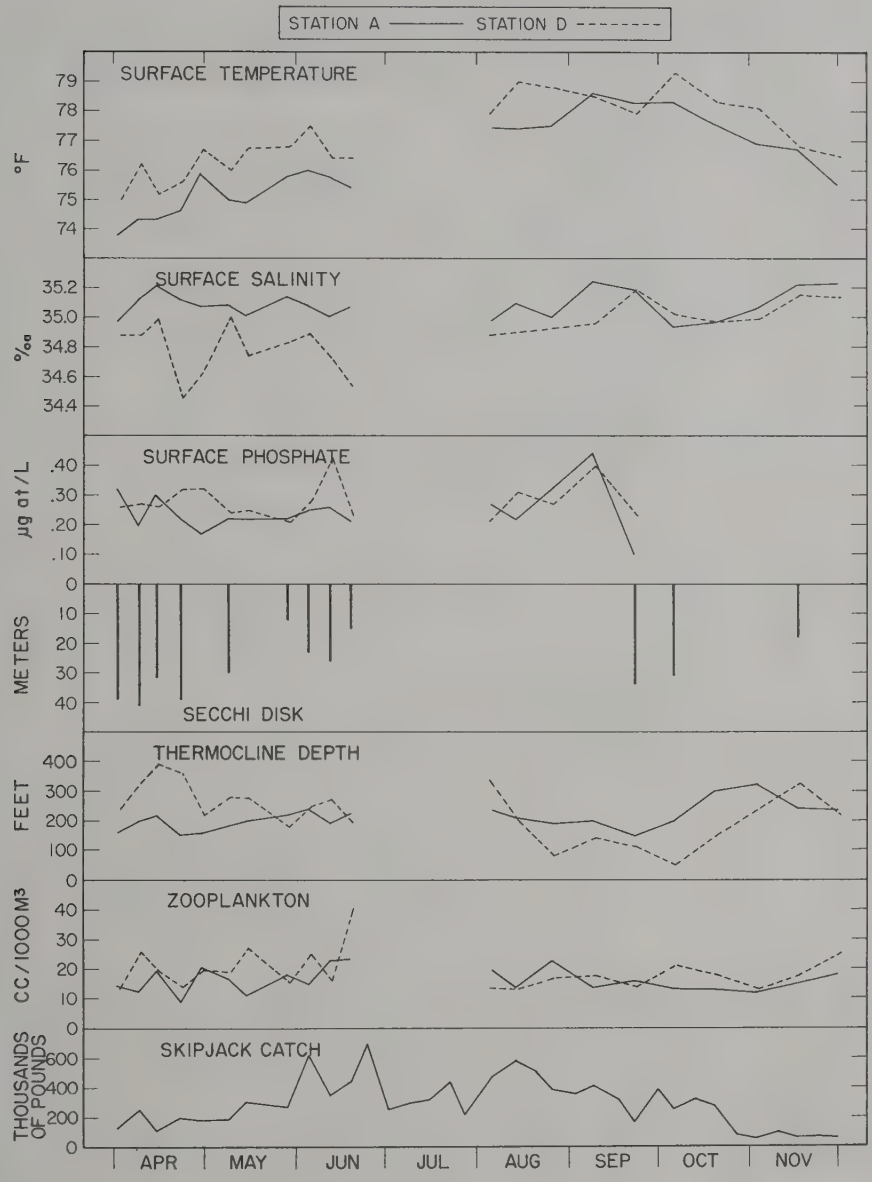

Figure 9.--Variations in surface temperature, surface salinity, surface phosphate, Secchi disk visibility (station A only), thermocline depth, and zooplankton volumes at stations A and D, located at the positions shown in figure 4, as compared with the weekly skipjack catch of the Hawaiian pole-and-line fishery for the same period of time, April to November 1953.

Table 5.--Results of correlation analyses based on repeated observations made at station D (position shown in fig. 4), comparing adjusted zooplankton volumes with several environmental factors and with the weekly skipjack catch of the Hawaiian area

X_1 variate	X_2 variate	Degrees of freedom	Correlation coefficient, r	P
Zooplankton volumes (cc/1000 m.^{3})	Surface temperature (°F)	19	-0.194	> 0.05
do.	Surface inorganic phosphate (μg at./L.)	14	-0.198	> 0.05
do.	Thermocline depth (feet)	19	-0.001	> 0.05
do.	Surface salinity (‰)	19	-0.275	> 0.05
do.	Skipjack catch (pounds per week)	19	0.219	> 0.05

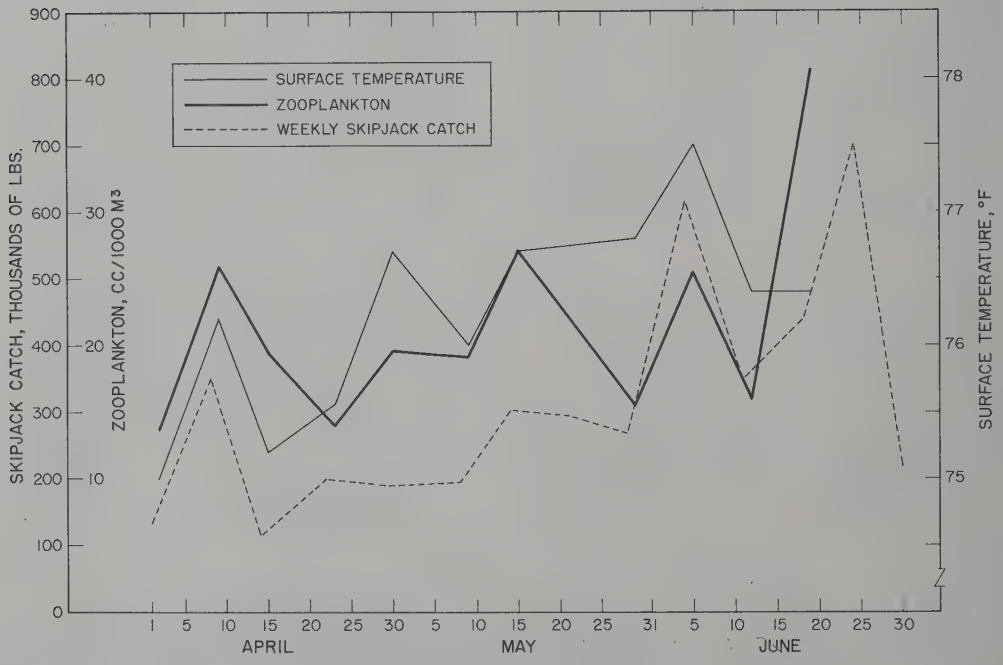

Figure 10.--Variations in surface temperature and zooplankton volume at station D, compared with the weekly Hawaiian skipjack catch for the period April 1 to June 30, 1953.

the more nutritious zooplankton per unit of water strained.

4. The night hauls yielded volumes averaging 1.49 times the volumes of day hauls. A method of adjustment was employed to reduce these differences associated with the hour of hauling.

5. A short series of experimental hauls indicated the superiority of night over day and 0- to 100-meter over 0- to 200-meter hauls in the catch of zooplankton and of fish larvae.

6. The distribution of zooplankton was remarkably uniform throughout the island waters. From an analysis of variance we concluded that there were no significant differences between cruises, between windward and leeward areas, or among six subareas.

7. Although the physical and chemical environments are also quite uniform in general respects, the surface currents are exceedingly complex and are characterized, particularly on the leeward side of the islands, by large vortices or eddies. We found no evidence that the eddies had any influence on the volume of zooplankton. Also evidence of the effects of upwelling, land drainage, or other littoral influence was obscure or lacking.

8. There was a trend of increasing zooplankton abundance from March to July; our data are not adequate, however, to provide a complete seasonal picture. Although surface temperature and the catch of the Hawaiian skipjack fishery also increase during the spring and early summer months, we doubt that there is a direct relationship among these variables.

9. Zooplankton volumes were not significantly correlated with water temperature, salinity, inorganic phosphate, thermocline depth, or skipjack catch. This lack of correlation between zooplankton and those factors considered most likely to have biological significance may indicate that other, more fundamental factors of the environment may be the causative agents for the variations observed.

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APPENDIX

Table 6.--Zooplankton volumes obtained on cruise 20 of the Hugh M. Smith, employing 1-meter nets of 30XXX grit gauze and oblique hauls to 200 meters depth (except as noted)

Station	Position		Date 1953	Time[1/]	Water strained, $m.^3$	Zooplankton, cc./1000 $m.^3$	
	North latitude	West longitude				Sample volume	Adjusted volume[2/]
1	23°43.5'	158°01.5'	3-9	0044-0117	1806.0	17.6	14.5
2	24°45.5'	158°02'	3-9	1047-1115	1051.7	12.1	14.7
3	25°53.5'	157°59'	3-9	2112-2142	1008.9	18.7	16.0
4	27°00'	158°04.5'	3-10	0925-0955	1185.1	13.8	16.3
5	28°04'	158°02'	3-10	2136-2207	1139.1	19.8	16.6
6	29°10.5	158°06'	3-11	0831-0900	1177.3	11.1	12.6
7	29°06'	155°02'	3-12	1431-1500	1095.3	14.1	16.5
8	28°03'	155°02'	3-13	0041-0111	1291.8	16.2	13.3
9	26°57'	155°01'	3-13	1307-1337	1509.2	12.7	15.4
10	25°54'	154°57'	3-13	2325-2357	1369.3	12.8	10.4
11	24°49'	154°58.9'	3-14	0930-1000	1311.0	10.4	12.3
12	23°33.5'	155°01.5'	3-14	2056-2127	1375.0	17.6	15.1
13	22°34'	155°01.5'	3-15	0601-0629	1466.4	7.3	7.4
14	21°28.5'	154°51'	3-15	1543-1612	1537.6	10.5	11.6
15	21°02'	154°20'	3-15	2355-0026	1332.6	23.3	19.0
16	20°35'	153°46'	3-16	0808-0838	1482.8	14.4	16.2
17	19°35.5'	154°13.5'	3-16	1747-1817	1547.8	14.7	14.7
18	20°02.5'	154°43.5'	3-17	0105-0135	1419.3	17.8	14.7
19	20°30'	155°19'	3-17	0846-0916	1410.1	14.5	16.7
20	21°50'	155°25.5'	3-17	2045-2114	1671.3	25.2	21.8
21	22°15.5'	155°59.5'	3-18	0358-0428	1562.2	15.9	14.6
22	22°37.5'	156°31.5'	3-18	1102-1132	1548.8	13.5	16.5
23	23°08.5'	156°59.5'	3-18	1815-1846	1728.6	17.0	16.4
24	23°37.5'	157°32.5'	3-19	0101-0132	1492.9	20.2	16.7
25a	23°33'	159°05.5'	3-19	1202-1232	1297.3	14.3	17.5
25	23°07'	158°30'	3-19	1936-2007	1401.7	21.0	19.0
26	22°42.5'	157°57'	3-20	0510-0540	1242.1	15.5	15.0
27	22°11.5'	157°22.5'	3-20	1519-1549	1323.4	12.5	14.1
28	21°46'	156°53'	3-21	0048-0118	1245.8	18.5	15.2
29	21°21.5'	156°17.5'	3-21	1003-1034	1461.0	14.8	17.8
30	20°55'	155°43.5'	3-21	1817-1847	1588.1	15.9	15.3
31	19°47'	156°13.5'	3-22	0503-0534	1890.2	15.4	14.9
32	20°09'	156°37'	3-22	1118-1148	1418.0	12.4	15.2
33	20°38'	157°05'	3-22	1727-1757	1511.9	13.0	13.2
34[3/]	21°05'	157°36.5'	3-22	2326-2357	1680.4	18.2	14.9
35	21°20.5'	158°18'	3-23	1910-1944	1693.7	24.3	22.7
36	22°01'	158°38'	3-24	0238-0308	1415.2	19.9	17.3
37	22°19.5'	159°03'	3-24	0833-0902	1464.0	14.6	16.6
37a	22°43.5'	159°38.5'	3-24	1533-1603	1654.8	13.6	15.3
38a	22°24.5'	160°13'	3-24	2144-2214	1385.0	23.1	19.4
38	21°29.5'	159°03'	3-25	1059-1129	1419.6	19.1	23.3
39	21°03'	158°36.5'	3-25	1732-1804	1879.6	11.5	11.7
40	20°35'	158°01.5'	3-26	0139-0209	1285.1	26.9	22.5
41	20°07.5'	157°32'	3-26	0824-0854	1217.4	14.0	16.0
42	19°36.5'	156°58.5'	3-26	1551-1621	1497.7	17.6	19.5

[1/] Apparent solar time.

[2/] Adjusted for day-night difference by the sine transformation method.

[3/] Surface haul in shoal water.

Table 6.--Zooplankton volumes obtained on Hugh M. Smith cruise 20 (Cont'd)

Station	Position		Date 1953	Time[1/]	Water strained, m^3	Zooplankton, cc./1000 $m.^3$	
	North latitude	West longitude				Sample volume	Adjusted volume[2/]
43	19°13'	156°31'	3-26	2145-2215	1105.2[4/]	20.7	17.3
44	18°49.5'	156°02.5'	3-27	0517-0547	1229.7[4/]	11.5	11.3
45	17°45'	155°27'	3-27	1553-1623	1335.5	10.3	11.4
46	18°04.5'	156°04'	3-27	2221 2251	1090.5	15.2	12.6
47	18°33.5'	156°40'	3-28	0558-0626	997.5	10.1	10.3
48	18°59'	157°06.5'	3-28	1207-1237	1384.5	17.6	21.6
49	19°25.5'	157°38'	3-28	1822-1852	1787.6	15.6	15.1
50	19°54'	158°07.5'	3-29	0032-0102	1536.6	15.4	12.6
51	20°21.5'	158°37.5'	3-29	0703-0732	1284.2	16.2	17.4
52	20°42'	159°15'	3-29	1354-1424	1554.9	17.0	20.3
53	21°16.5'	159°44'	3-29	2031-2102	1515.1	23.9	20.9
54	21°43.5'	160°17'	3-30	0242-0310	1475.4	25.9	22.4
54a	22°09'	160°59'	3-30	2125-2159	1788.9	20.0	16.9
55a	21°48'	161°29.5'	3-31	0348-0418	1593.4	25.9	23.4
55	21°21.5'	160°56'	3-31	1020-1048	1310.8	16.9	20.5
56	21°00'	160°25'	3-31	1621-1650	1364.4	18.6	20.0
57	20°31'	159°56'	3-31	2224-2253	1298.4	17.7	14.6
58	20°02'	159°21.5'	4-1	0500-0530	1561.6	17.7	17.1
59	19°36'	158°51.5'	4-1	1056-1124	1223.3	14.1	17.2
60	19°09'	158°22.5'	4-1	1701-1732	1297.3	15.6	16.1
61	18°42.5'	157°53'	4-1	2316-2346	1312.9	23.1	18.9
62	18°18'	157°25'	4-2	0536-0607	1152.3	12.8	12.8
63	17°45.5'	156°50'	4-2	1424-1453	1332.8	11.9	13.9
64	17°19'	156°19'	4-2	2136-2204	948.5	18.4	15.4

[1/] Apparent solar time.

[2/] Adjusted for day-night difference by the sine transformation method.

[3/] Surface haul in shoal water.

[4/] Based on an estimated meter reading.

Table 7.--Zooplankton volumes obtained on cruises 11, 12, and 13 of the Charles H. Gilbert, employing 1-meter nets of 30XXX grit gauze. Oblique hauls to 200 meters depth were made at the A and D stations; oblique hauls to 40 or 50 meters depth were made at the C station

Station	Position		Date 1953	Time[1/]	Water strained, $m.^3$	Zooplankton, cc./1000$m.^3$	
	North latitude	West longitude				Sample volume	Adjusted volume[2/]
Cruise 11							
5A	21°49.3'	157°32.2'	4-1	1342-1411	1616.7	11.7	14.6
7C	21°04.6'	157°31.5'	4-1	2149-2219	1376.2	42.3	-
8D	20°35.1'	157°32'	4-2	0209-0238	1388.4	16.9	13.7
9A	21°49.3'	157°32.4'	4-8	1317-1347	1594.1	9.7	12.2
11C	21°04.5'	157°31.6'	4-8	2142-2216	1991.6	31.3	-
12D	20°34.6'	157°32.5'	4-9	0155-0227	1936.5	31.9	25.9
13A	21°49.9'	157°32'	4-14	1259-1328	1318.3	15.3	19.5
15C	21°05.2'	157°32'	4-14	2158-2230	1319.8	25.9	-
16D	30°35'	157°32.2'	4-15	0220-0250	1740.4	23.7	19.5
17A	21°48.8'	157°32'	4-22	1300-1333	1815.1	7.0	8.9
19C	21°04.5'	157°32.2'	4-22	2149-2221	1059.2	31.6	-
20D	20°35'	157°32'	4-23	0156-0226	1480.3	17.2	14.0
21A	21°50.7'	157°31'	4-29	1248-1312	1024.1	16.2	20.7
23C	21°04.7'	157°31.9'	4-29	-	-	No sample	-
24D	20°35'	157°32'	4-30	0407-0436	1442.2	22.0	19.7
Cruise 12							
1A	21°50'	157°32'	5-8	1507-1533	1206.5	14.3	16.8
3C	21°06'	157°31.9'	5-8	-	-	No sample	-
4D	20°35'	157°32'	5-9	0244-0310	980.1	23.0	19.2
13A	21°50'	157°32'	5-14	1309-1337	1200.0	8.8	11.2
15C	21°04.6'	157°31.8'	5-14	2154-2226	1918.2	20.9	-
16D	20°35'	157°32.2'	5-15	0224-0251	1228.7	33.0	27.1
17A	21°45'	157°32'	5-28	1433-1503	1506.4	14.9	18.1
19C	21°05'	157°32'	5-29	0013-0041	1448.1	65.3	-
20D	20°35.2'	157°31.5'	5-29	0458-0530	1547.5	16.2	15.5
Cruise 13							
1A	21°50'	157°32'	6-4	1500-1536	2007.9	12.5	14.7
3C	21°04.1'	157°32'	6-4	2247-2319	2084.7	27.4	-
4D	20°35.3'	157°32.3'	6-5	0332-0402	2032.6	29.6	25.5
6A	21°50'	157°32'	6-11	1440-1513	2323.0	19.0	22.8
8C	21°05'	157°31.6'	6-11	2155-2226	2012.1	16.3	-
9D	20°35'	157°32'	6-12	0228-0256	1682.1	19.6	16.1
10A	21°50'	157°32'	6-18	1504-1532	1548.2	19.8	23.3
12C	21°05'	157°31.5'	6-18	2109-2136	1850.8	33.7	-
13D	20°35'	157°32'	6-19	0124-0155	2034.0	51.4	40.7

[1/] Apparent solar time.

[2/] Adjusted for day-night difference by the sine transformation method using the pooled regression coefficient (b = 0.1110).

Table 8.--Zooplankton volumes obtained on cruise 21 of the Hugh M. Smith, employing 1-meter nets of 30XXX grit gauze and oblique hauls to 200 meters depth (except as noted)

Station	Position		Date 1953	Time[1/]	Water strained, $m.^3$	Zooplankton, $cc./1000m.^3$	
	North latitude	West longitude				Sample volume	Adjusted volume[2/]
1D[3/]	20°33.8'	157°30.8'	8-4	1958-2027	1765.6	16.0	13.6
2C[3/]	21°10'	157°28'	8-5	0204-0230	1372.0	22.7	18.0
3B	21°25'	157°32.4'	8-5	0540-0608	1634.6	12.1	12.1
4A	21°52.9'	157°31.8'	8-5	1011-1041	1898.8	15.3	19.8
5	23°36.9'	157°30'	8-5	2342-0013	1698.9	16.2	12.2
6	23°13'	157°00'	8-6	0632-0702	2125.9	13.1	13.8
7	22°44'	156°21'	8-6	1309-1338	1709.4	11.2	14.6
8	22°18'	155°52'	8-6	1953-2023	1863.9	16.7	14.5
9	21°53'	155°20.5'	8-7	0249-0320	1470.5	18.4	15.0
10	21°26.1'	154°41'	8-7	1004-1033	1639.6	11.8	15.3
11	21°00'	154°16'	8-7	1555-1624	1579.6	13.0	15.0
12	20°34'	153°44.9'	8-7	2214-2245	1533.9	17.7	13.7
13	19°36.1'	154°10'	8-8	0702-0730	1846.6	10.7	11.8
14	20°06'	154°37.8'	8-8	1323-1353	1845.3	13.4	17.3
15	20°30.1'	155°12.2'	8-8	2018-2048	1485.0	21.2	17.6
16	21°00'	155°52.5'	8-9	0312-0343	1469.9	23.8	19.8
17	21°19.1'	156°21.1'	8-9	0850-0920	1694.9	12.3	15.1
18	21°48'	156°51.1'	8-9	1516-1546	1429.4	15.6	18.4
19	22°16.1'	157°24'	8-9	2133-2203	1395.1	25.4	20.1
20	22°39.7'	157°54.9'	8-10	0353-0423	1763.8	18.7	16.2
21	23°11.1'	158°26.6'	8-10	1019-1048	1310.5	28.8	37.6
22	23°34.6'	159°02.5'	8-10	1653-1723	1729.5	18.0	19.4
24	22°40'	159°41.8'	8-11	0310-0341	1715.0	19.8	16.5
25	22°22.2'	159°11'	8-11	0931-1002	1730.4	12.4	15.6
26	21°59.2'	158°38.8'	8-11	1615-1646	1569.1	11.2	12.3
27	21°17.4'	158°18.1'	8-11	2308-2342	2608.0	16.8	12.7
28A	21°52.2'	157°34.7'	8-13	1621-1651	1867.6	12.6	13.9
29B[3/]	21°24'	157°32.9'	8-13	2142-2212	1784.5	16.8	13.1
30C[3/]	21°03'	157°31'	8-14	0205-0236	1953.8	25.2	20.0
31D	20°33.1'	157°29.5'	8-14	0729-0800	1691.2	11.7	13.2
32	20°38.8'	157°01.1'	8-14	1202-1232	2145.7	7.9	10.5
34	20°12'	156°39.8'	8-14	2053-2123	1589.5	14.8	12.1
35	19°43'	156°12.2'	8-15	0317-0347	1940.8	17.7	15.0
36	18°50'	155°58.5'	8-15	1236-1304	960.1	17.5	23.1
37	19°20.8'	156°33.8'	8-15	1915-1946	1904.0	17.6	15.6
38	19°40'	157°05.1'	8-16	0133-0203	1613.9	16.2	12.5
39	20°07.4'	157°36.1'	8-16	0912-0943	1753.0	10.8	13.4
40	20°35.8'	158°06.2'	8-16	1759-1829	2104.3	13.5	13.2
41	21°02.1'	158°39.7'	8-17	0041-0111	1736.0	25.6	19.4
42	21°29.3'	159°13.2'	8-17	0702-0731	1605.6	14.0	15.4
43	22°20.2'	160°18.5'	8-17	1717-1747	2000.2	12.4	12.7
44	22°05.8'	160°56.9'	8-17	2334-0004	1815.1	25.7	19.4
45	21°38.1'	160°13.9'	8-18	0655 0726	1952.9	14.7	16.2
46	21°10.8'	159°46'	8-18	1305-1336	1714.3	11.6	15.1
47	20°50'	159°11.5'	8-18	2021-2051	1142.4	22.8	19.0
48	20°21'	158°32.8'	8-19	0431-0502	1452.6	17.6	16.0

[1/] Apparent solar time.

[2/] Adjusted for day-night difference by the sine transformation method.

[3/] Shallow hauls on Penguin Bank.

Table 8.--Zooplankton volumes obtained on Hugh M. Smith cruise 21 (Cont'd)

Station	Position		Date 1953	Time[1]	Water strained, $m.^3$	Zooplankton, cc./1000$m.^3$	
	North latitude	West longitude				Sample volume	Adjusted volume[2]
49	19°56.4'	158°10.3'	8-19	1109-1139	1668.6	14.1	18.7
50	19°27'	157°38.1'	8-19	1826-1857	1489.4	11.9	11.3
51	19°00'	157°08.1'	8-20	0052-0123	1135.3	24.0	18.2
52	18°36.1'	156°33.9'	8-20	0959-1028	1519.0	12.3	15.9
53	18°08.1'	156°01.1'	8-20	1741-1812	1398.5	13.5	13.5
54	17°40'	155°30'	8-21	0055-0127	2006.3	26.0	19.9
55	17°19'	156°10.9'	8-21	0724-0754	1996.1	10.6	11.9
56	17°46.2'	156°39.9'	8-21	1317-1347	1708.8	8.3	10.7
57	18°14'	157°08.5'	8-21	2006-2036	1920.7	24.1	20.5
58	18°44.2'	157°46'	8-22	0432-0502	2122.8	18.3	16.6
59	19°13'	158°21'	8-22	1120-1150	2357.7	8.2	10.9
60	19°38.1'	158°51.3'	8-22	1722-1752	2289.1	9.0	9.2
61	20°03.8'	159°16.1'	8-22	2253-2322	2175.4	24.8	18.8
62	20°30.5'	159°49.9'	8-23	0534-0604	1686.5	22.5	21.9
63	20°49.7'	160°27.5'	8-23	1221-1252	2082.0	15.4	20.4
64	21°24.8'	160°58'	8-23	1904-1933	1636.8	19.6	17.8
65	21°46.8'	161°25'	8-24	0117-0147	1851.8	21.4	16.5
66A	21°49.3'	157°31.8'	8-25	1338-1408	1646.4	17.6	22.5
67B[3]	21°22.5'	157°31.5'	8-25	1825-1855	1634.6	15.2	14.5
68C[3]	21°03.5'	157°29.8'	8-25	2235-2302	1458.2	32.4	24.8
69D	20°34.2'	157°29.6'	8 26	0352-0422	1558.7	19.7	17.1

[1] Apparent solar time.

[2] Adjusted for day-night difference by the sine transformation method.

[3] Shallow hauls on Penguin Bank.

Table 9.--Zooplankton volumes obtained on cruises 22, 23, and 24 of the Hugh M. Smith for stations A, C, and D on the sections east of Cahu, employing 1-meter nets of 30XXX grit gauze. Oblique hauls to 200 meters depth were made at the A and D stations; oblique hauls to 40 or 50 meters depth were made at the C station

Station	Position		Date 1953	Time[1/]	Water strained, $m.^3$	Zooplankton, $cc./1000m.^3$	
	North latitude	West longitude				Sample volume	Adjusted volume[2/]
Cruise 22							
5A	21°50.8'	157°32.8'	9-8	1317-1353	1506.4	10.7	13.5
7C	21°05.3'	157°32.0'	9-8	1945-2016	1253.3	27.8	-
8D	20°36.6'	157°30.8'	9-9	0023-0054	1384.1	22.8	17.7
18A	21°50.6'	157°30.8'	9-22	1314-1347	1557.3	12.6	15.9
20C	21°06.3'	157°30.6'	9-22	1941-2013	1539.8	21.6	-
21D	20°35.3'	157°29.5'	9-23	0011-0042	1386.0	18.0	13.9
Cruise 23							
1A	21°50'	157°30.4'	10-5	1429-1500	1624.5	10.6	12.9
3C	21°05'	157°31'	10-5	2132-2202	1496.6	63.7	-
4D	20°33.8'	157°31'	10-6	0210-0241	1425.3	26.2	21.2
14A	21°49.5'	157°31.2'	10-19	1405-1435	1289.9	10.5	12.9
16C	21°04.7'	157°31.2'	10-19	2137-2207	1743.3	29.5	-
17D	20°36'	157°30.2'	10-20	0157-0227	1385.9	22.3	18.1
Cruise 24							
1A	21°49'	157°31.4'	11-2	1617-1646	1280.1	11.0	12.0
3C	21°04.4'	157°31.7'	11-2	2238-2319	1427.6	10.0	-
4D	20°35'	157°30.6'	11-3	0320-0352	1499.5	15.1	13.0
14A	21°47.6'	157°31.9'	11-16	No sample	-	-	-
16C	21°04.9'	157°30.7'	11-16	2320-2348	1240.7	17.8	-
17D	20°37.1'	157°30.5'	11-17	0326-0356	1450.0	20.8	17.9
22A	21°50.4'	157°31.3'	11-30	1446-1515	1079.2	15.3	18.3
24C	21°06.5'	157°31.4'	11-30	2203-2232	1355.1	11.7	-
25D	20°35.6'	157°30.4'	12-1	0226-0256	1384.6	30.6	25.2

[1/] Apparent solar time.

[2/] Volumes at stations A and D adjusted by the sine transformation method using the pooled regression coefficient (b = 0.1110).

Table 10.--Zooplankton volumes obtained on cruise 26 of the Hugh M. Smith, employing 1-meter nets of 30XXX grit gauze and oblique hauls to 200 meters depth

Station	Position		Date 1954	Time[1]	Water strained, $m.^3$	Zooplankton, cc./1000$m.^3$	
	North latitude	West longitude				Sample volume	Adjusted volume[2]
5	20°33'	157°44'	5-29	0432-0507	1584.3	21.5	19.7
7	19°45'	156°18'	5-30	0435-0508	2193.5	24.1[3]	22.5
9	19°47'	157°23'	6-2	0430-0500	1460.6	29.5	27.0
11	19°51'	158°43'	6-3	0417-0448	1753.1	35.8[4]	32.8
13	18°12'	158°51'	6-4	0408-0440	1497.6	23.1	20.7
15	16°16'	160°28'	6-5	0359-0430	1398.2	16.7[5]	15.0
17	14°56'	162°16'	6-6	0356-0427	1512.2	19.8	17.8
19	13°54'	164°01'	6-7	0345-0418	1523.1	15.4	13.6
21	12°35'	165°45'	6-8	0353-0423	1337.7	33.6	29.5
23	11°11'	167°26'	6-9	0329-0400	1523.4	35.4	30.6
25	13°00'	168°13'	6-10	0332-0403	1456.0	21.2	18.3
25a	14°33'	168°25'	6-10	1626-1657	1420.4	16.4	17.9
27	16°01'	168°36'	6-11	0401-0432	1504.5	11.4	10.2
29	17°55'	169°37'	6-12	0355-0426	1331.9	30.1[6]	27.0
29a	19°37'	169°50'	6-12	1623-1653	1385.2	14.3	15.6
31	20°59'	169°12'	6-13	0359-0433	2022.9	19.0	17.1
33	21°05'	168°16'	6-14	0359-0430	1626.6	21.3	19.1
35	20°51'	166°48'	6-15	0407-0438	1628.4	22.2	19.9
37	21°14'	164°11'	6-16	0411-0442	1695.8	19.5	17.5
39	20°51'	161°59'	6-17	0423-0453	1655.0	20.9	19.1
41	21°17'	160°01'	6-18	0451-0522	1443.3	15.7	14.7

[1] Apparent solar time.

[2] Adjusted for day-night difference by the sine transformation method using the pooled regression coefficient (b = 0.1110).

[3] About 50 percent, by volume, Pyrosoma < 2 cm. longest dimension.

[4] About 15 percent, by volume, Pyrosoma < 2 cm. longest dimension.

[5] About 40 percent, by volume, Pyrosoma < 2 cm. longest dimension.

[6] About 15 percent, by volume, Pyrosoma < 2 cm. longest dimension.

Table 11.--Zooplankton volumes obtained on cruise 16 of the Charles H. Gilbert, employing 1-meter nets of 30XXX grit gauze and oblique hauls to the depth indicated

Station	Sample	Position		Date 1953	Time[1/]	Estimated depth of haul, m.	Water strained, $m.^3$	Zooplankton, $cc./1000m.^3$	
		North latitude	West longitude					Sample volume	Adjusted volume[2/]
15	1	20°59'	161°44'	8-11	2121-2155	191	1844.9	43.7	35.4
15	2	20°59'	161°43'	8-11	2158-2226	99	1330.1	56.1	44.5
15	3	21°00'	161°41'	8-11	2228-2305	200	1717.8	32.3	25.4
15	4	21°00'	161°40'	8-11	2308-2336	102	1250.7	69.4	54.0
16	1	21°11'	160°22'	8-12	0926-0958	204	1282.8	17.2	21.2
16	2	21°11'	160°21'	8-12	1000-1027	106	900.4	24.4	30.8
16	3	21°12'	160°19'	8-12	1029-1105	206	1551.7	15.8	20.1
16	4	21°12'	160°18'	8-12	1108-1138	102	1273.4	24.6	31.6

[1/] Apparent solar time.

[2/] Adjusted for day-night difference by the sine transformation method using the pooled regression coefficient (b = 0.1110).

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ZOOPLANKTON ABUNDANCE IN THE CENTRAL PACIFIC

PART II

BY JOSEPH E. KING AND THOMAS S. HIDA

FISHERY BULLETIN 118
From Fishery Bulletin of the Fish and Wildlife Service
VOLUME 57

UNITED STATES DEPARTMENT OF THE INTERIOR
FISH AND WILDLIFE SERVICE

UNITED STATES DEPARTMENT OF THE INTERIOR, Fred A. Seaton, *Secretary*

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ABSTRACT

During the period May 1951 to April 1954, 270 quantitative zooplankton hauls were made on 8 cruises to the central equatorial Pacific. The purpose was to obtain a measure of abundance of the standing crop of zooplankton as basic fish food, which measure might be used as an index to the relative productivity of different areas of the sea.

Night hauls yielded volumes averaging 1.57 times that of day hauls; this ratio varied considerably in different subdivisions of the current system. Differences related to the hour of hauling were reduced by an adjustment method based on the similarity of the sine curve and the diurnal variation in zooplankton catch.

The highest concentration of zooplankton was found at the Equator which, under the influence of the trade winds, is a region of divergence and upwelling. Although the greatest abundance of yellowfin tuna occurred just to the north in the convergent zone, there was a high degree of covariation in yellowfin and zooplankton in respect to the current system.

In the east-central Pacific, high concentrations of zooplankton were found along the northern boundary of the Countercurrent. As this is an area of shallow thermocline, high-phosphate water occurs within the photosynthetic zone and within the reach of wind-induced turbulence; conditions are therefore more favorable for plankton production than to the westward where the thermocline deepens.

Within the equatorial region there was a west-to-east gradient of increasing zooplankton abundance from 180° to 150° W. longitude, which varied directly with the yellowfin catch and the average wind velocity, and inversely with thermocline depth. East of 140° W. longitude the catch remained high, but varied irregularly.

Largest zooplankton volumes were taken in the quarter, July, August, and September, the lowest in January, February, and March. Catches were smaller in 1951, 1952, and 1953 than in 1950. There was some evidence of an increase in 1954.

It appears that the zooplankton was quick to respond to physical changes in the environment by dispersal or concentration following changes in the water mass. With an increase in breadth of the mixing zone at the equatorial divergence, there was a broadening of the zooplankton-rich zone; an increase in velocity of the Countercurrent was accompanied by a marked change in zooplankton distribution.

On long north-south sections, there were highly significant positive correlations between zooplankton volume and surface inorganic phosphate. Although the highest concentration of phosphate was found in the divergent zone at the Equator, agreeing in this respect with zooplankton, longitudinally and seasonally there was some evidence of an inverse relationship with zooplankton and yellowfin; this may have resulted from differences in the rate of utilization.

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ZOOPLANKTON ABUNDANCE IN THE CENTRAL PACIFIC, Part II

By JOSEPH E. KING, *Fishery Research Biologist*, and THOMAS S. HIDA, *Fishery Aid*

As a result of the last cruise of the *Carnegie* in 929 and the recent surveys of the Swedish Deep-ea Expedition, Scripps Institution of Ocea-iography, and the Pacific Oceanic Fishery Investi-ations (POFI) of the United States Fish and Vildlife Service, there has developed a general nderstanding of the vertical and horizontal urrents in the equatorial Pacific and their relation o marine life (Graham, 1941; Cromwell, 1953; erlov, 1953; Sette and others, 1954, Sette, 1955.[1] n brief, the moderate to strong east and southeast inds which prevail throughout most of the year the eastern and central equatorial Pacific, ogether with the Coriolis force of the earth's otation, produce a divergence of the surface aters at the Equator. Upwelling associated ith this equatorial divergence replenishes the upply of nutrients in the surface water and pro-des a suitable environment for the growth of hytoplankton and consequently for zooplank-n. Convergence and sinking of the surface aters, occurring between the Equator and e southern boundary of the Countercurrent, ay physically tend to concentrate the zooplank-n into a rich pasturage for small fish, squid, and her forage organisms. These in turn serve as od for the larger fishes such as the tunas, the oup of fish presently under study in these in-stigations. Many aspects of this complex ccession of events, such as the actual rates of oduction at the different eutrophic levels and e causes of variation in the system, are still to determined.

This is the second POFI report concerned with oplankton abundance in the central equatorial acific. The first report (King and Demond, 953) was based on four cruises in 1950 and 1951; e present paper contains an analysis of plankton data resulting from eight cruises in the period 1951 to 1954 and utilizes some of the observations from the earlier publication. With these extensive observations, we are now able to show more clearly how the abundance of zooplankton is a function of such environmental factors as the equatorial divergence, convergence, depth of the isothermal layer, and other features of the surface waters of the equatorial current system. Variations in the zooplankton are also shown to be related to hour of hauling, season, area (longitude), and direction and velocity of the tradewinds.

The chief purpose of these studies has been to obtain a quantitative measure of the standing crop of zooplankton, or basic fish food, which may be used as an index to the relative productivity of different areas of the sea. It is hoped that this information together with other oceanographic observations made simultaneously by these investigations will help explain variations in the distribution and abundance of tunas as determined by experimental and commercial fishing.

AREA AND METHODS

This study is based primarily on 270 collections obtained on 7 cruises (cruises 9, 11, 14, 15, 16, 18, and 19) of the motor vessel *Hugh M. Smith* and one cruise (cruise 15) of the motor vessel *Charles H. Gilbert* during the years 1951 to 1954. The approximate locations of the plankton stations are shown in figures 1 to 4. More exact positions together with date and hour of hauling, amount of water strained, and the zooplankton volumes for each cruise are given in appendix B, tables 6 to 13. Data collected on 4 earlier cruises in 1950 and 1951 (*Hugh M. Smith* cruises 2, 5, 7, and 8), and published in an earlier report (King and Demond, 1953), are also utilized in this study. Appendix A presents the results of a special study on variations in zooplankton abundance about an oceanic island. Hydrographic data collected on certain of these cruises have appeared in other POFI reports (Cromwell, 1951, 1954; Austin, 1954a,

[1] Also paper by O. E. Sette entitled, Nourishment of Central Pacific ocks of Tuna by the Equatorial Current System, to be published in the oceedings of the Eighth Pacific Science Congress (Manila); and unpub-ed manuscript of T. S. Austin entitled, Review of Central Equatorial cific Oceanography, 1950–52.

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1954b; Stroup, 1954; Murphy and Shomura, 1955; and Iversen and Yoshida, 1956).

For the most part, sampling was done along north-south lines since in this portion of the central Pacific the current flow is zonal, i. e., tends to be parallel to the Equator. With this type of circulation, it was believed that maximum information from hydrographic and plankton observations would be obtained with station lines normal to the flow. The northernmost station was located at 31°54′ N. latitude, 119°46′ W. longitude and the southernmost station at 8°58′ S. latitude, 121°28′ W. longitude. In an east-west direction the sampling extended from 110° W. to the 180 meridian, a distance of 4,200 miles.

The majority of the collections were taken wi 1-meter (mouth diameter) nets with body (fro and middle sections) of 30XXX silk grit gau (apertures averaging 0.65 mm. in width), rear se tion and bag of 56XXX silk grit gauze (apertur averaging 0.31 mm. in width). For comparati purposes 6 hauls were made on cruise 15, *Hugh M Smith*, with a 1-meter net of 56XXX grit gau body and 72XXX grit gauze (apertures averagi 0.21 mm. in width) rear section and bag.

Oblique hauls of approximately 30 minut

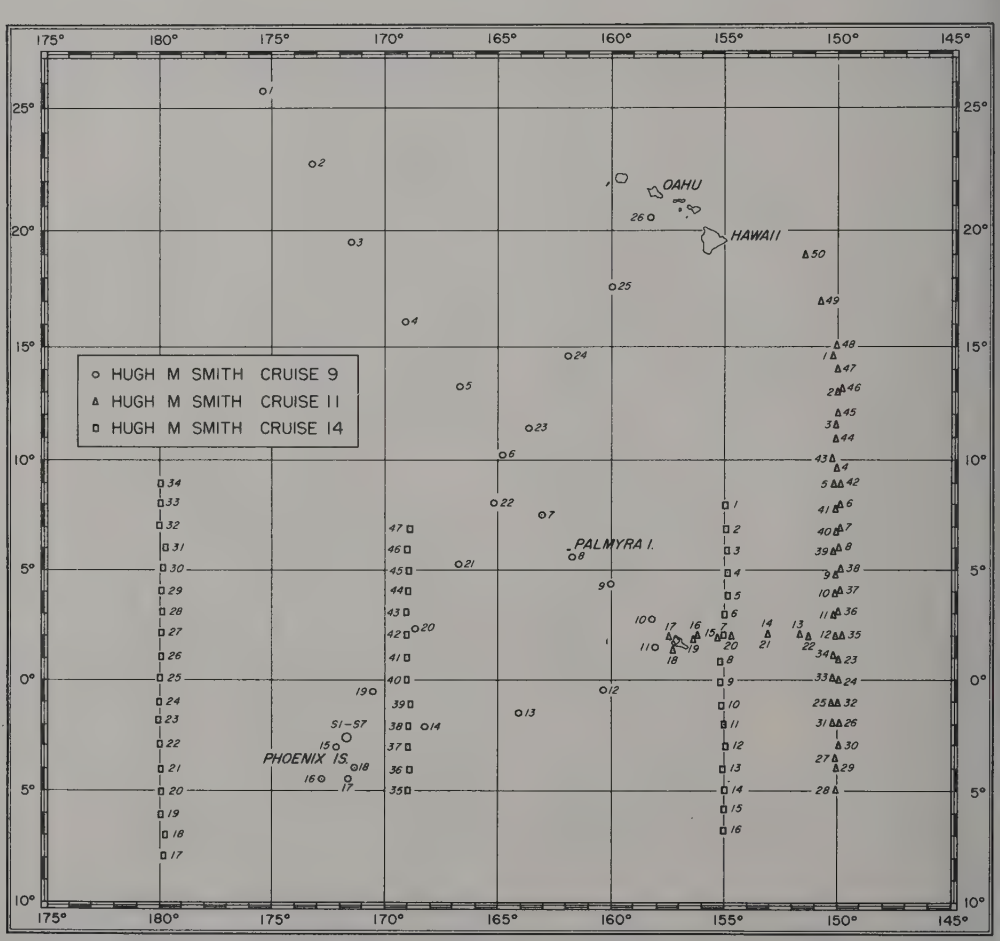

FIGURE 1.—Plankton-station positions of *Hugh M. Smith* cruises 9 (May–July 1951), 11 (August–October 1951), and (January–March 1952).

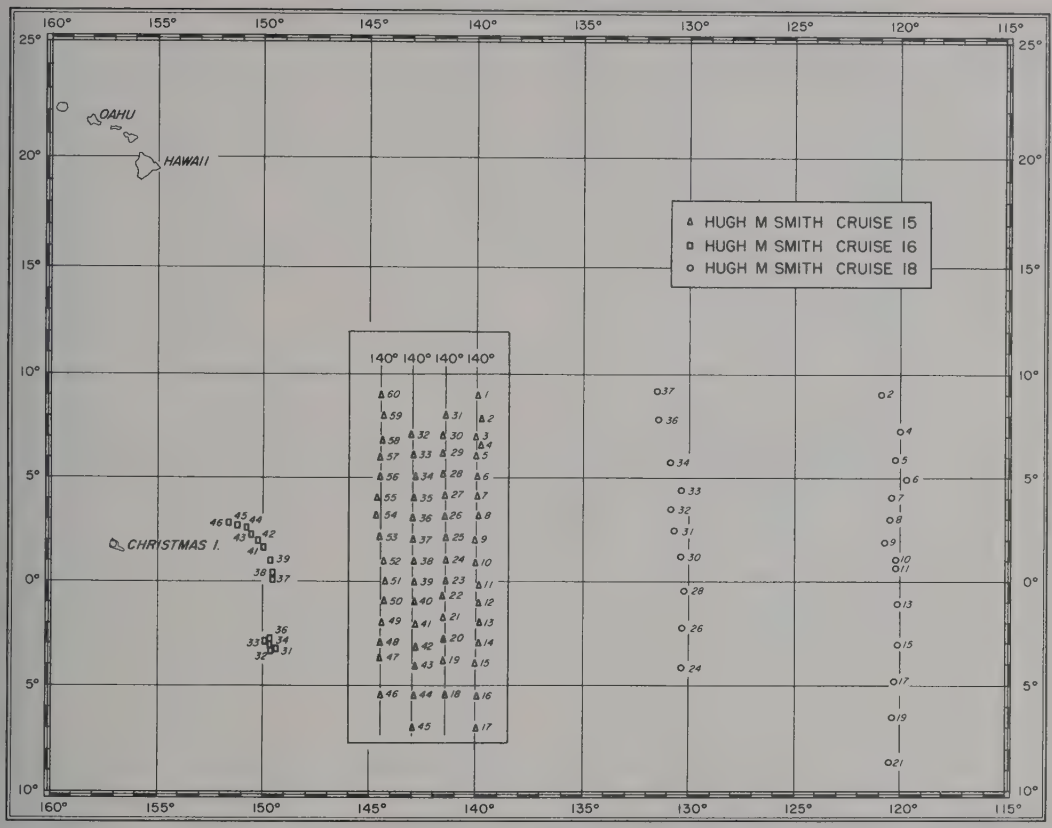
160° 155° 150° 145° 140° 135° 130° 125° 120° 115°
25° 20° 15° 10° 5° 0°
OAHU
HAWAII
CHRISTMAS I.
HUGH M SMITH CRUISE 15
HUGH M SMITH CRUISE 16
HUGH M SMITH CRUISE 18
140° 140° 140° 140°

FIGURE 2.—Plankton-station positions of *Hugh M. Smith* cruises 15 (May–June 1952), 16 (August 1952), and 18 (October–November 1952).

duration to a depth of about 200 meters were employed on most cruises. On the *Hugh M. Smith* cruise 14, multiple-net horizontal hauls were made at 7 stations. Methods of hauling and calculation of sampling depth and amount of water strained have been explained in previous reports (King and Demond, 1953; King and Hida, 1954).

TREATMENT OF SAMPLES IN THE LABORATORY

First the few organisms with longest dimension greater than 2 cm. were removed from each sample, identified as precisely as possible, and their displacement volume determined. Then the volume of the remainder and bulk of the sample, i. e., those organisms with longest dimension less than 2 cm., was determined. In measuring the displacement volume, the plankton was poured in a draining sock of 56XXX grit gauze, to filter off the preserving liquid. When the sample stopped dripping, it was transferred to a graduated cylinder of appropriate size (usually 50 or 100 ml. capacity). By means of a burette, a known volume of water was added to the drained plankton. The difference between the volume of the plankton plus the added liquid and the volume of liquid alone was recorded as the displacement or wet volume of that portion of the sample.

Following the procedure at our laboratory, the volume of all organisms less than 2 cm. in length plus the volume of organisms 2 to 5 cm. in length that might be considered of significant nutritional value [2] were combined to give a single volume

[2] We consider annelids, chaetognaths, crustaceans, cephalopods, and fish to be of significant nutritional value, and siphonophores, medusae, ctenophores, heteropods, and tunicates as non-nutritious. Bigelow and Sears (1939) and also Clarke (1940) considered the crustaceans, chaetognaths, and mollusks as being of high nutritive value. It is our judgment, that the heteropod mollusks of the family Pterotracheidae, which are of common occurrence in the plankton of the tropical and subtropical Pacific, do not belong with this group because of their watery structure and should be classed with the non-nutritious forms.

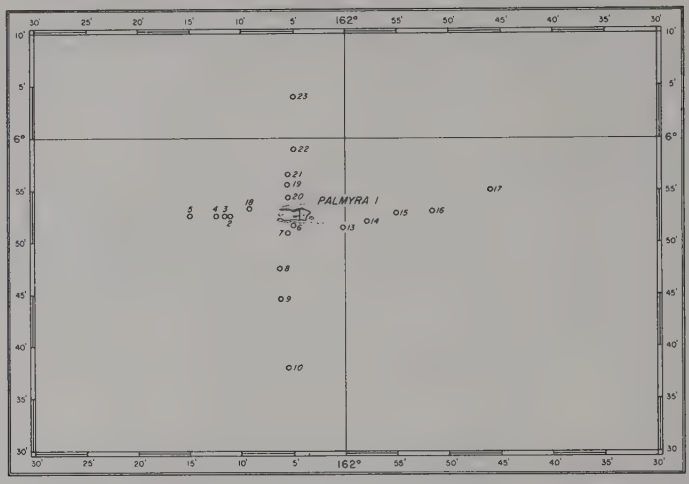

FIGURE 3. -Plankton-station positions of *Hugh M. Smith* cruise 19 (January 1953).

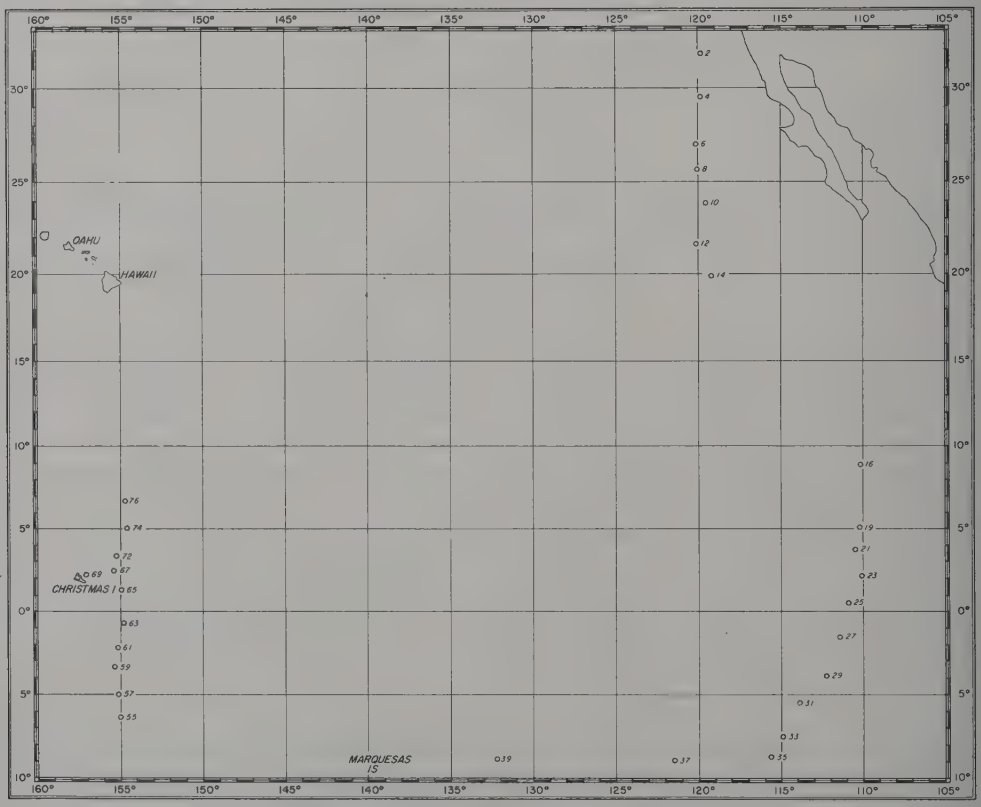

FIGURE 4.—Plankton-station positions of *Charles H. Gilbert* cruise 15 (February–April 1954).

measurement for each sample. This figure was divided by the estimated amount of water passing through the net to obtain the volume of zooplankton, as food, per unit of water strained.

The contents of 6 samples obtained on cruise 15 of the *Hugh M. Smith* were counted for the purpose of comparing the catches obtained with 30XXX and 56XXX grit gauze nets. The counting method was essentially the same as that employed by King and Demond (1953).

The zooplankton volumes have been examined by simple statistical analysis where it was apparent that a test of significance would aid in interpreting the results. Group comparisons, correlation, regression, and analysis of variance have been used, following Snedecor (1946). Since it was not possible to design the sampling program to isolate sources of variation determined from a priori knowledge, in our analysis of variance we have been limited to a single criterion of classification with subsampling, i. e., a "completely randomized" design (Snedecor, 1946: 240–241). While the method is conveniently adaptable to unequal subsampling, it is less sensitive and less efficient than one based on a more advanced experimental design. Inferences from the analysis are modified occasionally by consideration of the 0.95 fiducial intervals of means based on their individual variances.

Although the distribution of the zooplankton volumes is slightly skewed to the left and the means correlated to some degree with the standard deviations, in tests of significance we have used untransformed data. Initially, various lots of data were transformed to logarithms and employed in statistical tests. The results and conclusions in each were the same as those reached through an analysis of the untransformed data. Snedecor (1946: 42, 252) states that little bias is introduced into the analysis of variance and the "t" test by moderately skewed populations. We assume, therefore, that the moderate abnormality of the zooplankton population has little effect on the inferences made in this report.

EFFECTS OF MESH SIZE ON ZOOPLANKTON CATCH

Early in our zooplankton studies we adopted the 1-meter, 30XXX grit gauze net (average aperture width 0.65 mm.) as being the best suited for our purposes. Nets of this mesh size retain the tuna eggs (of about 0.80 mm.) and tuna larvae, the capture of which was one object of our sampling,[3] but allow almost all phytoplankton to pass through the net; consequently, a relatively "clean" sample of zooplankton is obtained. Some preliminary hauls indicated that, at least on this occasion, nets of 56XXX (aperture width 0.31 mm.) and 72XXX grit gauze (aperture width 0.21 mm.) retained some of the larger phytoplankton as well as micro-zooplankton, thus making analysis and sorting of the sample more difficult.

A comparison of the catch of Clarke–Bumpus samplers (with 5-inch mouth opening), equipped with 56XXX nets, with the catch of 1-meter, 30XXX nets indicated that neither the sample volumes nor their variance differed appreciably between the two types of gear (Hida and King, 1955). The greater retention by the finer mesh of small Copepoda, Foraminifera, Appendicularia, and invertebrate eggs was at least partially compensated for in the large net of coarser mesh by the less successful avoidance of the net by the larger organisms.

To obtain a more precise comparison of the catching abilities of 1-meter nets of 30XXX and 56XXX grit gauze, 6 special hauls were made on the *Hugh M. Smith* cruise 15. A pair of consecutive hauls, the first with a 30XXX net and the second with a 56XXX net, were completed at 3 stations on 140° W. longitude: station 45, at 7° S. in the South Equatorial Current, a "poor zone" in respect to zooplankton; station 52 at 1° N., in the "rich zone" of the equatorial divergence; and station 60 at 9° N. in the Equatorial Countercurrent, which in the eastern Pacific is also a "rich zone" (p. 377). All were oblique hauls to an estimated 200 meters' depth and all were taken at night.

As to volume, the catch of the 56XXX nets was about 1¼ to 1¾ times that of the coarser meshed 30XXX nets (table 9, appendix B). Unfortunately, one of the samples contained an estimated 30 percent by volume of very small salps which were not separated from the bulk of the sample and therefore complicated the volume comparison. In respect to the number of organisms, the finer meshed nets retained 3 to 5 times

[3] Results are reviewed in unpublished manuscript of W. M. Matsumoto entitled, Description of Larvae of Four Species of Tuna and Their Distribution in Central Pacific Waters.

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TABLE 1.—*Average number of zooplankters per unit of water strained and percentage composition of the catch obtained with 30XXX grit gauze (apertures 0.65 mm.) and 56XXX (apertures 0.31 mm.) grit gauze at three stations of* Hugh M. Smith *cruise 15 in June 1952*

Organisms	Station 45 (7°00′ S.)				Station 52 (1°00′ N.)				Station 60 (9°00′ N.)			
	Average number per 100 m.³		Percent composition		Average number per 100 m.³		Percent composition		Average number per 100 m.³		Percent composition	
	30XXX	56XXX	30XXX	56XXX	30XXX	56XXX	30XXX	56XXX	30XXX	56XXX	30XXX	56XXX
Foraminifera	214	1,257	9.0	8.8	156	1,665	3.4	7.3	16	299	0.5	3.
Radiolaria	0	35	0	0.2	104	0	2.3	0	0	0	0	0
Coelenterata	51	70	2.2	0.5	139	166	3.1	0.7	317	220	8.9	2.
Chaetognatha	489	1,188	20.4	8.3	521	1,332	11.5	5.9	269	439	7.6	4.
Annelida	0	70	0	0.5	0	33	0	0.1	32	140	0.9	1.
Copepoda	1,072	9,745	44.8	68.0	2,811	17,145	62.1	75.4	1,473	6,924	41.5	68.
Ostracoda	51	244	2.2	1.7	17	233	0.4	1.0	0	439	0	4.
Euphausiacea	274	349	11.5	2.4	174	333	3.8	1.5	48	220	1.3	2.
Amphipoda	17	35	0.7	0.2	17	0	0.4	0	0	0	0	0
Shrimp	0	0	0	0	17	0	0.4	0	16	0	0.5	0
Crustacean larvae	17	175	0.7	1.2	0	67	0	0.3	16	60	0.5	0.
Mollusca	43	140	1.8	1.0	35	266	0.8	1.2	111	299	3.1	3.
Tunicata	17	978	0.7	6.8	330	466	7.3	2.0	1,061	778	29.9	7.
Fish	51	0	2.2	0	52	67	1.1	0.3	0	40	0	0.
Eggs	77	0	3.2	0	156	932	3.4	4.1	0	120	0	1.
Miscellaneous	17	35	0.7	0.2	0	33	0	0.1	190	120	5.4	1.
Total for sample	2,390	14,321	100.1	99.8	4,529	22,738	100.0	99.9	3,549	10,098	100.1	100.

as many plankters as the coarser meshed nets. Table 1 gives for each sample the average number per unit (100 m³) of water strained and the percentage composition for the major constituents. It appears that the greatest difference in the catch of the 2 nets is in the larger numbers of foraminifers and copepods retained by the 56XXX net.

The results show a marked difference between the 2 nets in average size (volume) of individual organisms in the catch (table 2); plankters in the catch of the 30XXX net were about 3 times as large as those taken by the 56XXX net, primarily because of the difference in catch of small copepods such as the microcalanoids and cyclopoids. As the result of an increased catch of the larger zooplankton forms (coelenterates, salps) and fewer of the smaller forms (foraminifers, chaetognaths), both nets yielded larger organisms, on the average, at the northernmost station (station 60).

TABLE 2.—*Average size (i. e., volume of catch divided by the number of organisms) of zooplankters captured in 30XXX and 56XXX grit gauze nets at three stations of* Hugh M. Smith *cruise 15 in June 1952*

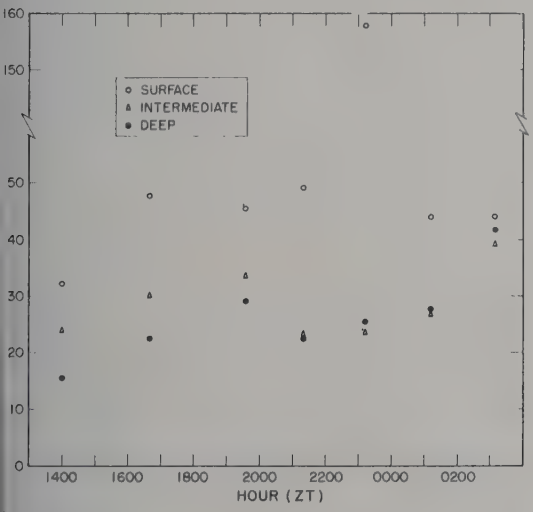
Item	Station 45 (7°00′ S.)		Station 52 (1°00′ N.)		Station 60 (9°00′ N.)	
	30XXX	56XXX	30XXX	56XXX	30XXX	56XXX
Average number of organisms per 100 m.³	2,390	14,321	4,529	22,738	3,549	10,098
Volume of catch, cc. per 100 m.³	3.22	5.07	6.98	12.21	8.04	9.09
Average size of organism, cc.x10⁻⁴	13.5	3.5	15.4	5.4	22.7	9.0

It is obvious that these 2 nets of different mesh exercised a strong size-selection in sampling the zooplankton community. The question as to which net-size yielded the most reliable measure of abundance of zooplankton as potential fish food cannot be decided from the few data presented here. It is generally known that no one net or other sampling device will quantitatively sample the entire zooplankton community, and therefore the investigator must choose the method and gear that in his opinion will contribute the most toward his particular objective. Our objectives, to obtain a representative sample of the larger zooplankton forms and to retain all tuna eggs and larvae with a minimum of mesh-clogging, were realized, we believe, with the use of 1-meter nets of 30XXX grit gauze.

VARIATION IN CATCH WITH SAMPLING DEPTH

On 7 stations of *Hugh M. Smith* cruise 14 in February 1952, horizontal hauls were made simultaneously at 3 levels with open 1-meter nets. The hauls were of 1-hour duration; the nets were lowered and raised at the start and end of the haul as rapidly as possible to minimize contamination of the intermediate and deep samples. All 7 stations were off Canton Island in the South Equatorial Current between 2°41′ S. and 2°45′ S. latitude at about 172° W. longitude, and were occupied consecutively between 1315 and 0338 hours of February 9–10, 1952. Although the prima

urpose of the sampling was to investigate the undance and vertical distribution of tuna eggs d larvae in this area, some information was ob-ined on the variation in zooplankton volumes ith depth and with time over a 14-hour period. According to the results shown in table 8B ppendix B) and figure 5, at each of the 7 stations 1 to S7) the largest volume of zooplankton was ken in the surface net. At station S5, hyperid mphipods were apparently swarming at the sur-ce and resulted in an unusually large catch.



URE 5.—Variation in zooplankton volumes with hour f hauling, as obtained with horizontal hauls at the depths: surface, intermediate (105–120 meters), and leep (210–240 meters); *Hugh M. Smith* cruise 14 ebruary 9–10, 1952.

e other samples were of mixed composition, ical of this area. At four of the 7 stations intermediate net, fishing just above the rmocline at a depth of 105 to 120 meters, ght more than the deep net fishing below the rmocline at 210 to 240 meters. These results generally similar to those obtained with rke-Bumpus samplers (employing 56XXX s) on a series of 30 stations extending from N. to 7° S. latitude along 150° N. longitude da and King, 1955). The surface samples of latter series averaged 60.7 cc./1,000m.^{3}, the rmediate samples (from within the thermo-e) averaged 29.2, and the deep samples (at –300 meters) averaged 16.6.

Although this sampling period of about 14 hours is not adequate to demonstrate the diurnal cycle, there is some evidence of an "evening rise" between 1400 and 2000 hours, followed by a drop in catch at the intermediate and deep levels and then what is possibly the start of a "morning rise" at these levels. The parallel variation ($r=0.837$, $P<0.05$) in volume of catch at the intermediate and deep levels is of interest and suggests that the zooplankton at these depths was behaving differently from that at the surface in response to varying illumination.

ADJUSTMENT FOR DIURNAL VARIATION

The hour of hauling provides an important source of knowledge of the variation in quantitative measurements of zooplankton abundance. Presumably, the difference between day and night hauls is due either to an augmentation in the upper strata of water by upward migration of the plankton at night or to a reduction in catch in the daytime owing to the greater ability of the plankton to dodge the net when there is light, or to a combination of the two. In some areas of the tropical Pacific the day-night difference is sufficiently great, if no correction is applied, to obscure the geographical and seasonal differences which are of primary interest in this study.

Significant differences in zooplankton volume, associated with latitude, were observed among the night samples and not among the day samples on cruises 5 and 8 of the *Hugh M. Smith* in the central equatorial Pacific (King and Demond, 1953). In Hawaiian waters the volumes of night hauls have averaged about 1½ times the volumes of day hauls (King and Hida, 1954). In the present instance during the 6 cruises in the equatorial region on which sampling was conducted around the clock, night hauls yielded volumes about 1½ times the volume of the day hauls (table 3), while the twilight hauls were intermediate in average volume.[4] Some of the variation among cruises, as shown in table 3, may be due to differences in season, longitude, and range of latitude sampled. Variations in the night/day ratio associated with the current system will be discussed later.

[4] For purposes of this comparison we designated the twilight hours as 0430 to 0730 and 1630 to 1930, which periods include sunrise and sunset and the beginning and end of twilight as specified by the American Nautical Almanac; the day period was thereby limited to 0730–1630 and the night to 1930–0430 hours.

TABLE 3.—*Differences in the average volumes of day, night, and twilight hauls and in the night/day ratios for six cruises of the Hugh M. Smith in the equatorial Pacific*

Cruise No.	Cruise period	Number of samples	Zooplankton—mean volume, cc./1000 m.³				Night/day ratio
			Night hauls	Day hauls	Twilight hauls	Total	
2	Jan.–Feb. 1950	[1] 24	45.5	24.0	26.6	[1] 33.6	1.90
5	June–Aug. 1950	51	40.3	27.9	37.1	34.7	1.44
8	Jan.–Mar. 1951	87	30.7	18.2	23.9	23.9	1.69
11	Sept.–Oct. 1951	[2] 23	41.7	32.1	33.2	[2] 36.0	1.30
14	Jan.–Mar. 1952	47	30.7	22.8	25.3	24.5	1.34
15	May–June 1952	60	50.6	31.6	36.9	39.9	1.60
Average			39.9	26.1	30.5	32.1	1.54

[1] Sections A and C only (King and Demond, 1953, table 1).
[2] Northbound section only.

On the majority of cruises sampling was conducted around the clock so that there were about equal numbers of night and day stations. Under this system there rarely were more than two day stations or two night stations occupied consecutively. On certain cruises, however, such as cruise 18 of the *Hugh M. Smith*, and cruise 15 of the *Charles H. Gilbert*, hauls were made at about the same hour throughout the cruise; e. g., on cruise 18 all hauls were made near midnight, on cruise 15 between 1900 and 2000. The resulting data are most useful for within-cruise comparisons, but some modification is necessary if they are to be compared or combined with the results of the other cruises.

An adjustment to remove the effect of diurnal change in zooplankton catch was described by King and Hida (1954). The method is based on the similarity of diurnal variation in zooplankton abundance to the curve of the sine function when midnight is equated to the angle whose sine is +1.0. The zooplankton volumes are increased or lowered dependent on the hour of hauling and adjusted to 0600 or 1800 hours, when the sine=0. Since illumination is the major factor controlling the diurnal migration of plankton (Kikuchi, 1930; Cushing, 1951), solar time is used in the calculations.

The method as originally designed was applied to zooplankton volumes from the Hawaiian Islands area, where the geographical variation was slight and the night/day ratio rather uniform from cruise to cruise. On the long sections crossing the Equator we found considerable variation in the night/day ratio associated with latitude and the current system (p. 380), and the geographical variation is much greater than in the Hawaiian area. Although these factors lessen the accuracy an effectiveness of the method, it still provides reasonably good correction for day-night diffe ences as judged by the significance of the "t values and the night/day ratios for the adjuste volumes (table 4), and has therefore been applie to the equatorial data.

TABLE 4.—*Regression coefficients (b), "t" values a probability values for the sine transformation method adjustment for 5 cruises of the* Hugh M. Smith *in t equatorial Pacific.*

[A comparison of the night/day ratios for the zooplankton volumes before a after adjustment indicates the general validity of the method].

Cruise No.	Number of samples	b	t	P	Night/day ratio	
					Before adjustment	After adjustment
5	51	0.0941	2.077	<0.05	1.44	1
8	87	.1534	5.046	<0.001	1.69	0
11	23	.0842	1.251	>0.05	1.30	0
14	47	.1340	3.472	<0.01	1.34	1
15	60	.1186	3.228	<0.01	1.60	1

Throughout this report we have employed t adjusted volumes in examining the variation zooplankton abundance with respect to speci features of the current system, with longitud and with season. The data from cruises 5, 11, 14, and 15 of the *Hugh M. Smith* were a justed by individual cruise. A pooled regressi coefficient (b=0.1248) calculated from the co bined data of these 5 cruises that covered lar areas of the equatorial Pacific during which t stations were visited consecutively regardless the time of day or night, was used in adjusti the volumes of cruises 2, 7, 9, 16, 18, and 19 the *Hugh M. Smith* and of cruise 15 of the *Char H. Gilbert*. On the latter cruises, sampling w not conducted around the clock, or there were t few data to be adjusted by individual cruis Unadjusted volumes for the *Hugh M. Sm* cruises 2, 5, 7, and 8 have previously been pu lished (King and Demond, 1953). The adjust volumes for these cruises are provided herew in table 14 (appendix B).

DESCRIPTION OF THE ENVIRONME

The general pattern of the Pacific equato current system has been described by Sverdr and others (1942:708–712). In brief, the ma surface currents of this region are the North a South Equatorial Currents flowing toward west, and the eastward flowing Equatorial Co

rcurrent sandwiched in between. Although
e boundaries of the Countercurrent may vary
eridionally with longitude and season, its south-
n and northern boundaries ordinarily occur
ear 5° N. and 10° N. latitude in the mid-Pacific.
he South Equatorial Current is therefore on
oth sides of the Equator while the North Equa-
rial Current is confined entirely to the Northern
emisphere. As previously stated, the Equator
the site of upwelling resulting from divergence
the surface waters. It is also the location of
e newly discovered subsurface Equatorial Un-
rcurrent flowing to the eastward (Cromwell
d others, 1954). The region between the
quator and the southern boundary of the Coun-
rcurrent is a zone of convergence. Under
rtain conditions, as described by Cromwell
953) and Cromwell and Reid (1956), a sharply
fined convergence or "front" [5] may be formed
the South Equatorial Current between the
quator and the southern boundary of the
ountercurrent.

The motion of these currents is either directly
indirectly the result of wind stress on the
rface of the ocean, and it is logical that varia-
ns in these currents are a reflection of variations
the prevailing winds or "trades."

The Climatic Charts of the Oceans (U. S.
eather Bureau, 1938), based on averages of 50
ars of observations, provide a general picture
the velocity and direction of prevailing winds
the equatorial Pacific. Average wind condi-
ns for the months of March and August,
ich represent the extremes of the seasonal
riation, are shown in figure 6.

In the region of our zooplankton studies (110°
to 180° long.), the charts show longitudinal
l latitudinal as well as seasonal variations
the tradewinds. In an east-west direction
ng the Equator there is a general decrease in
ensity from Beaufort force 3 and 4 east of 160°
longitude to force 1 and 2 west of that merid-
. Between 100° W. and 140° W. the south-
t trades are dominant (>60 percent constant)
ng the Equator in all months of the year.
tween 140° W. and 160° W. they are dominant
m May to January; between 160° W. and
0° they are only of importance from July to
October. At other months of the year the resultant wind at the Equator is from the east between 140° W. and 160 W., and from the northeast between 160° W. and 180°.

North of the Equator in the region of the Countercurrent, the period of strongest winds is from December to May when the northeast trades prevail. At other months of the year the winds are light and variable; in the eastern part of the region, from 120° W. to 140° W., the southeast trades exert a slight influence. Longitudinally the northeast trades reach their highest velocity between 140° W. and 170° W. longitude.

According to the wind drift model of Cromwell (1953), convergence and sinking of the surface waters will occur to the north of the Equator in the South Equatorial Current during a south or southeast wind, and conversely to the south of the Equator under the influence of a north or northeast wind. A pronounced convergence or front has been encountered south of the Equator on only one of the many POFI hydrographic and fishing surveys. This is not surprising in view of the slight influence of north or northeast winds at the Equator in the eastern and central Pacific. Evidence of convergence north of the Equator has been observed, though, on several occasions.

When the generally westward current near the Equator has a northward component, as during southeast trade winds, we anticipate that the zone of greatest zooplankton abundance will be north of the Equator, due both to the physical displacement of the organisms and the time lag in their development, with the peak of abundance occurring somewhere in the zone of convergence between the region of upwelling and the southern boundary of the Countercurrent. With a prevailing northeast wind the zooplankton maximum should theoretically occur to the south of the Equator and, with an east wind, more nearly on the Equator or with a double peak.[6]

In summary, then, as a result of the direction and relative high velocity of the trade winds, we expect to find larger concentrations of zooplankton

[5] efined by Cromwell (1953) as "a pronounced oceanic convergence," by Cromwell and Reid (1956) as "a narrow band along the sea surface s which the density changes abruptly" and "the surface temperature ient is often of the order of degrees per 1/100 mile."

[6] Murphy and Shomura (1953b) have shown that the latitudinal variation in the zone of best-yellowfin-catch also coincides with differences in the prevailing winds. Fishing sections along 120° W. and 130° W. longitude, associated with southeast winds, indicated the peak abundance to be north of the Equator; the catch along 155° W. and 169° W., associated with variable winds, showed the peak abundance to be nearly centered on the Equator, while a section along 180°, associated with northeast winds, indicated the peak of yellowfin abundance to be displaced to the south.

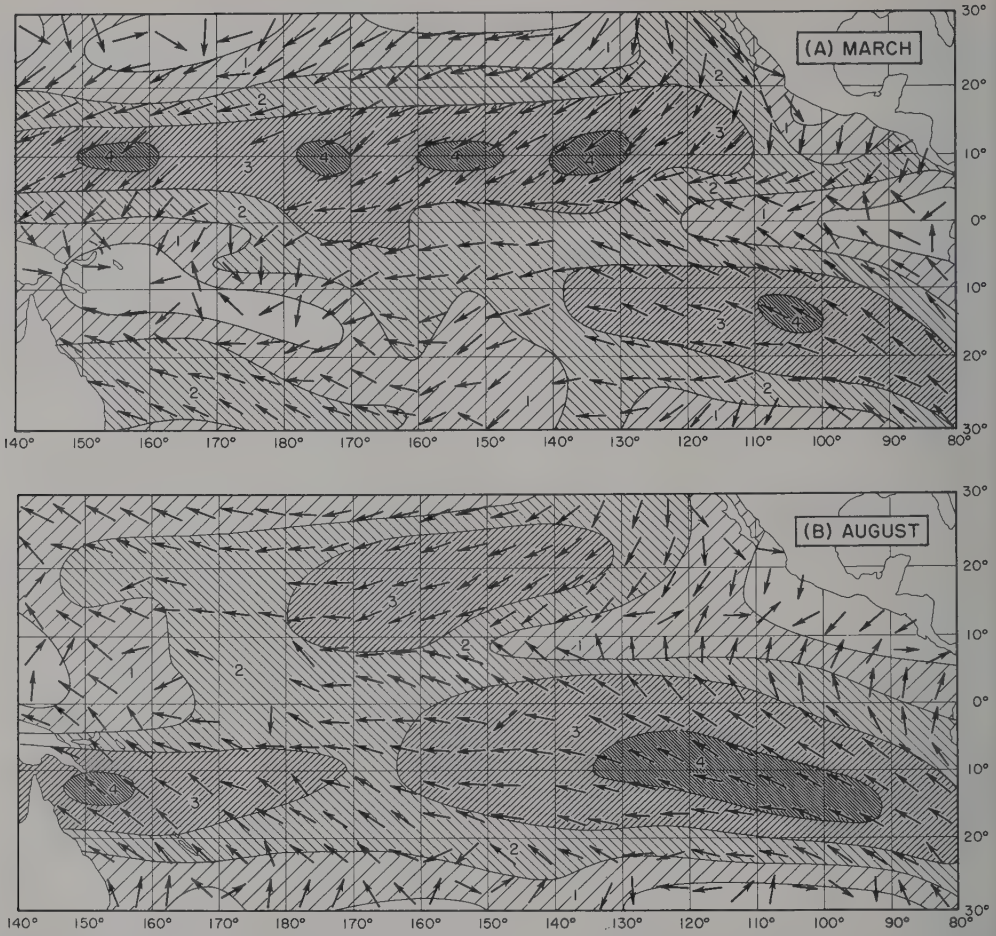


FIGURE 6.—Resultant direction and force of surface winds in the central equatorial Pacific during March (A), a mont of light and variable winds on the Equator but strong northeast trades in the region of the Countercurrent, an during August (B), a month of strong southeast trades on the Equator and light winds along the Counter-curren [From Atlas of Climatic Charts of the Oceans, U. S. Weather Bureau, 1938. Arrows show resultant wind directio computed for each 5-degree unit area. Shadings indicate gradations of resultant velocities scaled in Beaufort units wind force.]

east of 160° W. than to the west of that longitude and also more to the north of the Equator than to the south. A narrow convergent zone which theoretically should concentrate the zooplankton is most likely to occur east of 160° W., and particularly east of 140° W., because of the prominence of the southeast trades in that region.

ZOOPLANKTON AND THE CURRENT SYSTEM

Within the range of latitude sampled, there ar certain natural subdivisions of the environmen which may be established on the basis of th current structure. These may be defined a follows: (1) the North Equatorial Current fro

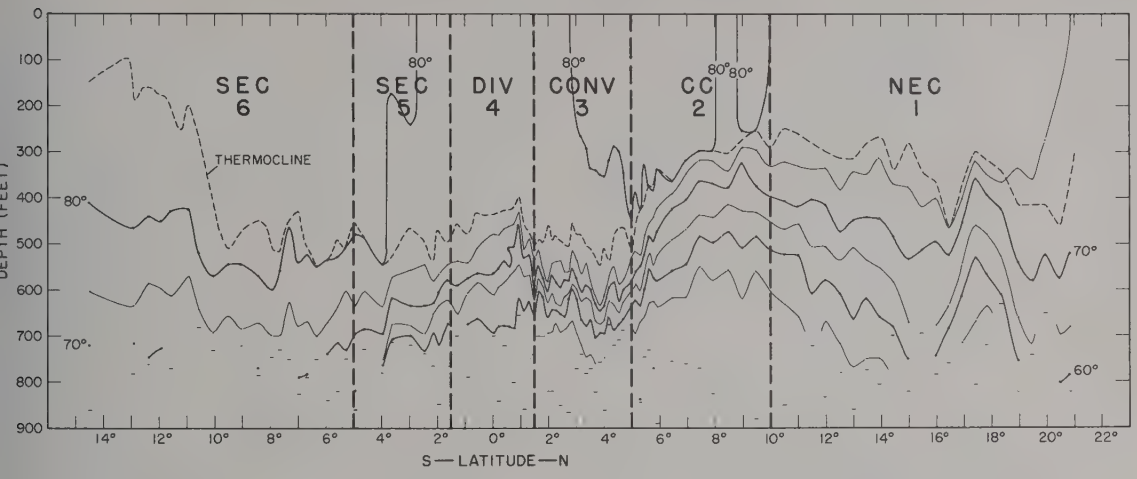


FIGURE 7.—Vertical temperature section (adapted from Cromwell and Austin, 1954, figure 28) based on bathythermograph observations along 172° W. longitude, made February 27–March 12, 1951, on *Hugh M. Smith* cruise 8, showing the boundaries of the 6 areas used in this study in relating variations in zooplankton abundance to particular features of the equatorial current systems.

he northern limit of our sampling to the northern oundary of the Countercurrent, a region of elatively shallow thermocline; (2) the Counter- urrent with its boundaries being determined at he time of each crossing from vertical temperature ections, a region with shallow thermocline to the orth, deepening to the south; (3) a zone of onvergence in the South Equatorial Current xtending (according to our definition) from the outhern boundary of the Countercurrent to 1½° N. latitude, a region of deep thermocline; (4) a one of divergence and upwelling in the South Equatorial Current along the Equator from 1½° N. to 1½° S. latitude, evidenced by a doming of the sotherms, a reduction in surface temperature, and n increase in surface inorganic phosphate; (5) he South Equatorial Current from 1½° S. to 5° S. atitude, a region of deep thermocline; and (6) he South Equatorial Current from 5° S. latitude to he southern limit of our sampling (about 14° S.), region of shoaling thermocline to the south. Figure 7 shows the boundaries of these six areas uperimposed on a vertical temperature section ased on bathythermograph observations along 72° W. longitude.

When the zooplankton volumes, adjusted for the lay-night variation but disregarding differences elated to longitude and season, are combined ccording to these natural divisions of the current ystem, we obtain the distribution shown in figure 8, with the greatest concentration of zooplankton occurring at the Equator (1½° N. to 1½° S.) in the region of divergence. Average volumes for the areas just north of the Equator, i. e., the convergent zone and the Countercurrent were considerably higher than those for the corresponding areas south of the Equator. The North Equatorial Current and the South Equatorial Current at the southern extent of our sampling were equally poor in zooplankton. From an analysis of variance we conclude that the

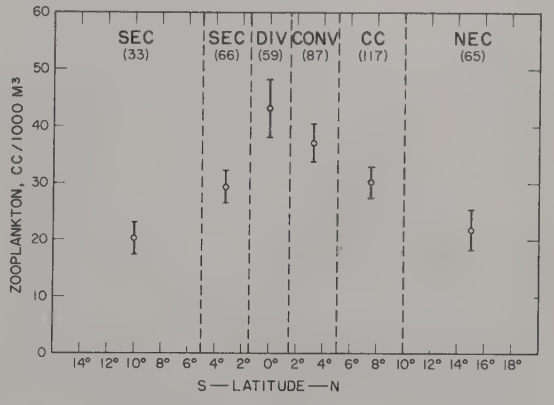


FIGURE 8.—Variations with the current system in zooplankton volumes (adjusted) for longitudes 120° W. to 180°, with the limits of the 0.95 fiducial interval shown for each mean. [The number of samples for each area is indicated in parentheses].

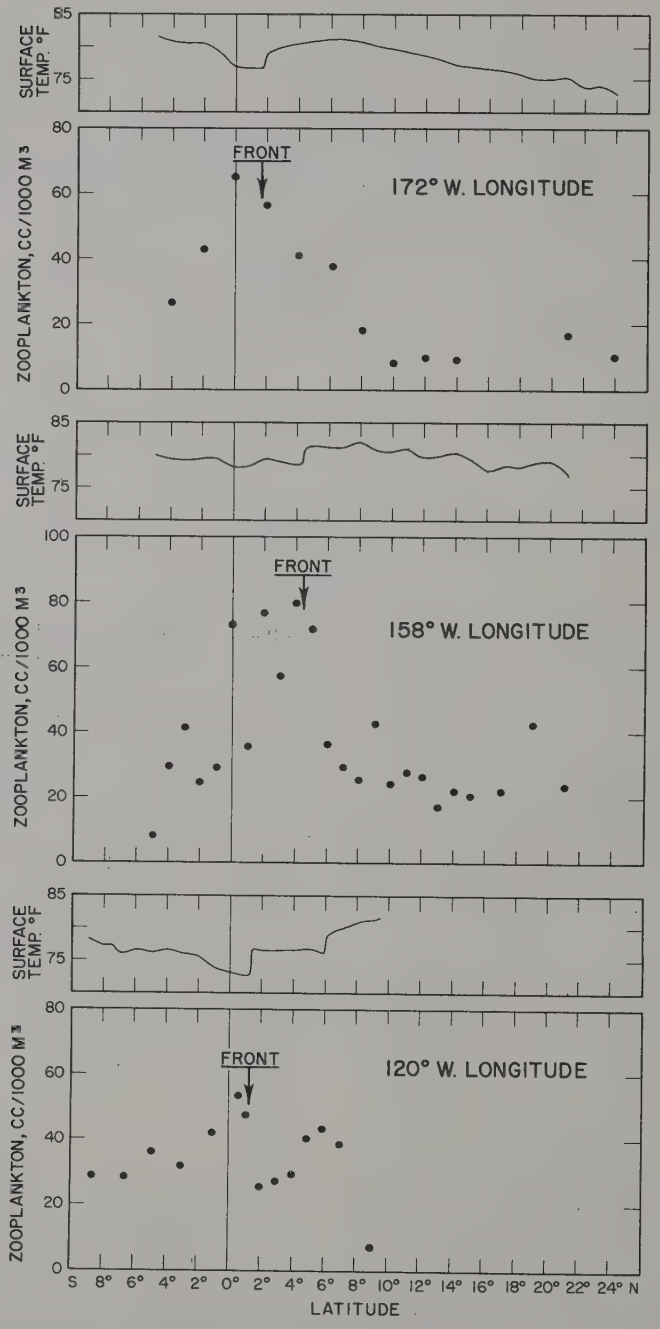


FIGURE 9.—Relation of an oceanographic front to the distribution of zooplankton (adjusted volumes) as demonstrated by 3 series of stations along 172°, 158°, and 120° W. longitude of *Hugh M. Smith* cruises 2, 5, and 18, respectively.

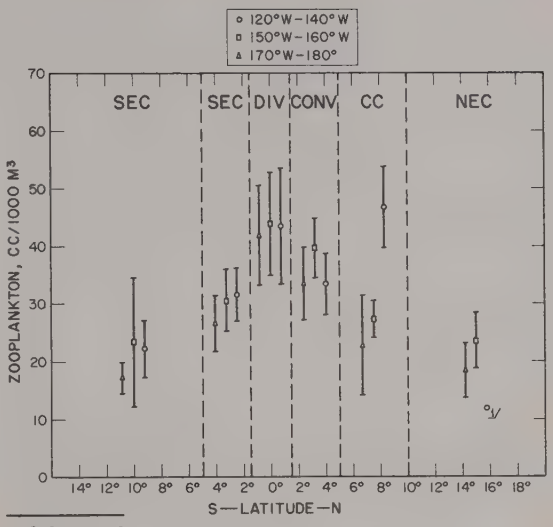
differences among subdivisions of the current system are highly significant ($F=4.08$ $P<0.01$). The degree of overlap in the 0.95 fiducial intervals of the means is shown in figure 8.

The asymmetrical distribution of the zooplankton in respect to the Equator results, we believe, from the prevalence of the southeast trades during most of the year. The occurrence of the zooplankton peak at the site of the divergence in an area of newly upwelled water, rather than in "older" water to the north or south of the Equator, is somewhat surprising and may be evidence that, on the average, the northward and southward components in the westerly surface current at the Equator are slight compared with the rate of development of zooplankton.

The distribution of zooplankton around well-marked fronts suggests a causal relation. Three well-defined fronts have been observed on POFI cruises in the convergent or transition zone to the north of the Equator. On all three occasions strong southeast winds were experienced between the Equator and the region of the front. The latitudinal variation in zooplankton abundance as related to these fronts is illustrated in figure 9 for the three series of stations along 120° W., 158° W., and 172° W. longitude. On each of the three meridians the zooplankton abundance peaks south of the front and drops off sharply to the north.

VARIATION WITH LONGITUDE

To examine the east-west variation in zooplankton abundance in respect to divisions of the current system as previously defined, the adjusted volumes were first combined by 10-degree intervals of longitude disregarding season. Because of the shortage of data for some subdivisions, longitudes 170° W. and 180°; were then combined as were 150° W. and 160° W.; 120° W. was grouped with 130° W. and 140° W. The latitudinal zooplankton distributions in the two western regions, 150° W.–160° W. and 170° W.–180°, are essentially alike (fig. 10) with peak abundance occurring at the equatorial divergence, and with the convergent zone next in importance. In the eastern region (120° W.–140° W.), we find the highest average volume in the Countercurrent with the area of divergence second in rank. Only in the Countercurrent are there significant differences among longitudes, as indicated by the



[1] Only 1 sample.

FIGURE 10.—Longitudinal and latitudinal variations in the distribution of zooplankton volumes (adjusted) with the data segregated into three longitudinal groups and in accordance with natural features of the current system. The limits of the 0.95 fiducial interval are indicated for each mean.

lack of overlap in the 0.95 fiducial intervals of the means. And it is only in the eastern Pacific that production in the Countercurrent equals that of the divergent zone. While these apparent relations may change with further sampling and more complete seasonal coverage, we believe the results are logical in view of longitudinal variations in thermocline depth and winds.

As previously mentioned, toward the northern boundary of the Countercurrent in the eastern and central Pacific, there is a doming in the isotherms (figs. 7 and 17) and the thermocline is relatively shallow; consequently high-phosphate water is within the photosynthetic zone and within the reach of wind-induced turbulence. To the westward the thermocline deepens (Sverdrup and others, 1942: 708), reducing the likelihood of such enrichment. Figure 11 shows the relation of the average zooplankton volumes for the range of latitude 8° N. to 11° N., and the depth of the 70° isotherm for four meridians (140° W., 150° W., 160° W., and 170° W. long.). The chosen range of latitude (8° N.–11° N.) includes the doming in the isotherms at the northern boundary of the Countercurrent and represents the zone of most shallow thermocline in the tropical Pacific. The results indicate a highly significant

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inverse correlation ($r = -0.688$, $P < 0.01$) from east to west between zooplankton volume and depth of the 70° isotherm which lies within the thermocline. We believe this relation results because of differences in depth of high-phosphate water and amount of wind-induced enrichment, although there is some evidence (Moore and others, 1953) that a shallow thermocline may act as a thermal floor in controlling the vertical distribution of zooplankton. Probably the correct explanation cannot be obtained from our 200-meter hauls but would require a detailed study employing horizontal hauls with closing nets.

In general, zooplankton volumes from the eastern and central longitudes were higher than in the west. When the volumes are combined by 10-degree intervals of longitude for the Countercurrent with boundaries at about 5° N. and 10° N. latitude, and for the South Equatorial Current from about 5° N. to 5° S. latitude, we obtain the results shown in figure 12. In the Countercurrent there was a sharp peak in abundance at 140° W. longitude and a marked reduction both to the east and west. In the South Equatorial Current, bracketing the Equator, the highest average volume occurred at 150° W., but there was actually little variation with longitude between 120° W. and 170° W. The few collections taken along 110° W. were omitted from this comparison. We should point out that the means shown for 120° W., 130° W., and 180° are based on few samples with poor seasonal coverage.

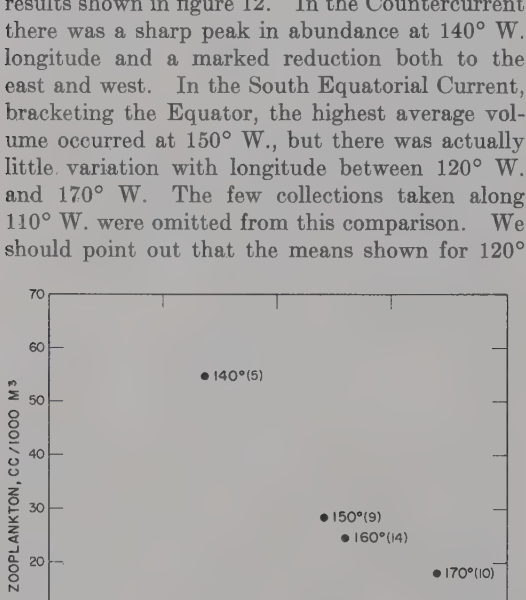


FIGURE 11.—Variation of zooplankton volume (adjusted) with depth to the 70° F. isotherm for the latitudes 8° N.–11° N. on longitudes 140° W. to 170° W. [Number of stations providing zooplankton and temperature observations are shown in parentheses.]

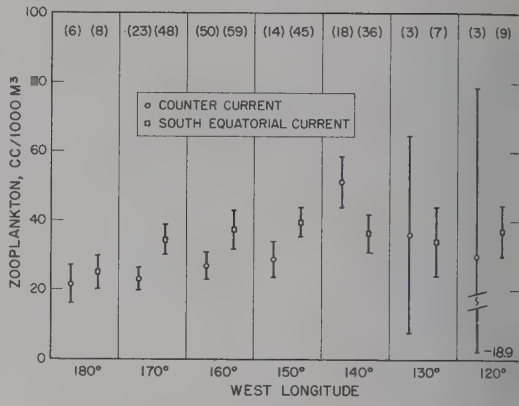


FIGURE 12.—Longitudinal variation in zooplankton volumes (adjusted) for the Countercurrent, extending from about 5° to 10° N. latitude, and for the South Equatorial Current from about 5° N. to 5° S. latitude. The limits of the 0.95 fiducial interval are shown for each mean. [The number of samples for each area is indicated in parentheses.]

From an analysis of variance we conclude that differences between the two subdivisions of the current system are highly significant ($F = 5.57$, $P < 0.01$), but that differences associated with longitudes are not significant ($F = 0.76$, $P > 0.05$). Despite the statistical evidence that the differences among longitudes are not significant (with the exception of that between 140° W. and 150° W. in the Countercurrent, as indicated by lack of overlap of the 0.95 fiducial intervals of the means), the general picture of decreasing zooplankton abundance from 140° W. to 180° parallels certain changes in the environment. Along the Equator with decrease in wind velocity from east to west we may expect a corresponding decrease in upwelling and enrichment of the surface waters; in the region of the Countercurrent, the possibility of enrichment through wind-induced turbulence decreases from east to west with the deepening in thermocline.

DIFFERENCES AMONG SEASONS AND YEARS

It was pointed out by King and Demond (1953) that the zooplankton volumes taken in January and February in the equatorial Pacific averaged significantly less than those obtained in June and

July. With further sampling the results showed a rather uniform level of abundance for the 9-month period April through December (King, 1954) with a reduction from January to March. Figure 13 shows the results of our sampling to date for the Countercurrent and for the equatorial region of the South Equatorial Current with the volumes combined, irrespective of longitude, into four quarterly periods of 3 months each. In the Countercurrent the highest average volume was obtained for the second quarter, April, May, and June, which occurs during the period when northeast trade winds are predominant at those latitudes. Along the Equator the last six months of the year, the period of strong southeast trade winds (Crowe, 1952) averaged higher than for the first two quarters. From an analysis of variance, however, we conclude that the differences among seasons are not statistically significant ($F=1.87$, $P>0.05$), but again differences between subdivisions of the current system are highly significant ($F=8.38$, $P<0.01$).

If we segregate the data geographically according to divisions of the current system and seasonally into two 6-month periods, i. e., (1) January to June, which includes roughly the time of lightest winds along the Equator in the central Pacific, and (2) July to December, the period of

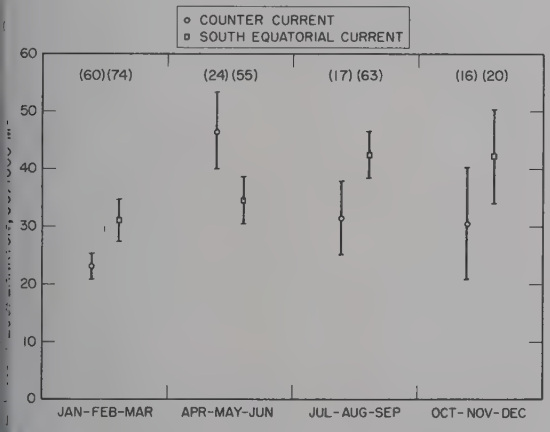


FIGURE 13.—Seasonal variations in zooplankton volumes (adjusted) for the Countercurrent with boundaries at about 5° N. and 10° N. latitude, and for the South Equatorial Current from about 5° N. to 5° S. latitude; longitudes 120° W. to 180° combined; the limits of the 0.95 fiducial interval are shown for each mean. [The number of samples for each season and each subdivision of the current system is indicated in parentheses.]

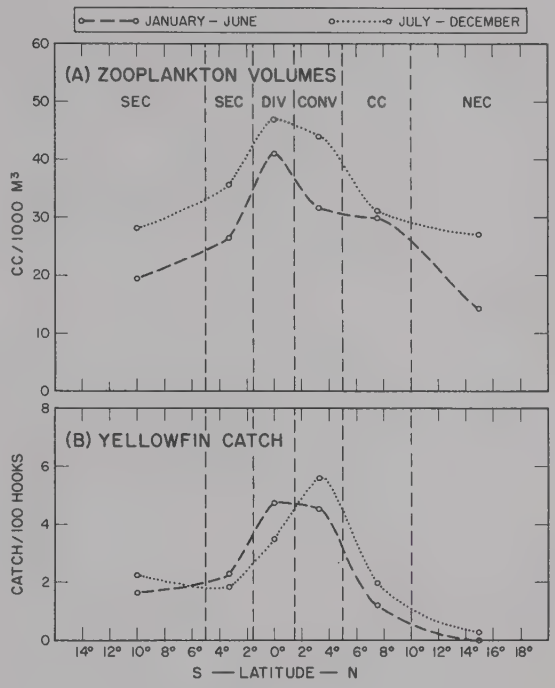


FIGURE 14.—Variation with the current system in (A) zooplankton volumes (adjusted) and (B) yellowfin longline catch for the two 6-month periods, January–June, a period with northeast or light and variable winds, and July–December, a period of prevailing southeast trade winds (in the central equatorial Pacific).

strong southeast trades, we find an interesting difference (fig. 14A). In both groups, the peak abundance in zooplankton occurred at the Equator, but during the latter half of the year under the influence of the southeast trades the abundance continued high into the convergent zone. When the data from this zone are examined by means of the "t" test we find, however, that the mean for January–June is not significantly different ($P>0.05$) from the mean for July–December.

Our data indicate that along the Equator there was considerable difference in zooplankton abundance among years. Figure 15 presents average zooplankton volumes for the Countercurrent and the equatorial region of the South Equatorial Current which were visited repeatedly from 1950 to 1954. From an analysis of variance we may conclude that differences between the two subdivisions of the current systems are highly significant ($F=27.60$, $P<0.01$), differences among years are also highly significant ($F=7.33$, $P<0.01$), but

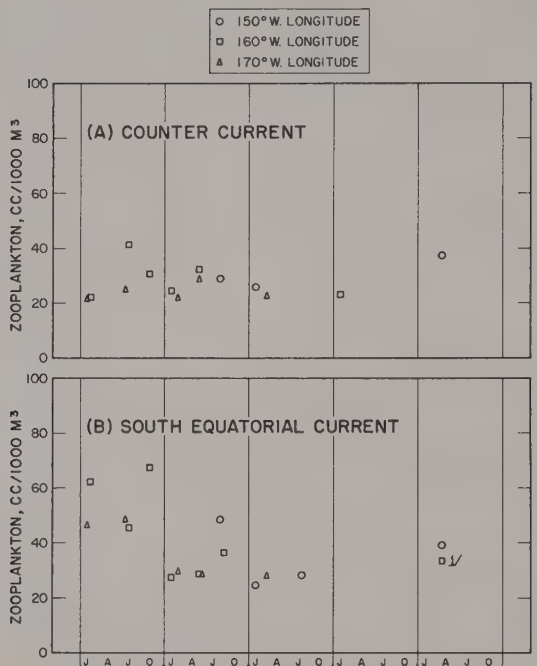


FIGURE 15.—Annual variation in zooplankton abundance for the most frequently sampled longitudes of (A) the Countercurrent with boundaries at about 5° N. and 10° N. latitude, and (B) the South Equatorial Current from about 5° N. to 5° S. latitude.

differences among longitudes are not significant ($F=0.178$, $P>0.05$). It is obvious that the differences among years are derived principally from variations within the South Equatorial Current. The general agreement among longitudes is in line with results from the previous tests.

Along the Equator the volumes for longitudes 160° W. and 170° W. averaged considerably higher in 1950 than in subsequent years. On longitude 150° W., August–September 1951 provided much higher volumes than January and August 1952. In both the Countercurrent and the South Equatorial Current there is some indication of a rise in 1954.

Possibly related changes are evidenced in other environmental factors. From a study of the rather sparse rainfall records available for the central equatorial Pacific,[8] Austin concludes that in the year 1950 the precipitation at Fanning Island (located at about 4° N. latitude, 159° W longitude) was unusually low and infers that southeast winds predominated throughout the year.[9] On the other hand, judging by the climatological summaries, the years 1951, 1952, and 1953 may be considered as normal years in respect to rainfall and also, by inference, in respect to winds i. e., with northeast and variable winds during the first 6 months and east to southeast winds during the latter half of the year. Therefore the year of highest apparent productivity in the zone of interest coincided with the year in which the southeast trades appear to have been unusually vigorous, thus perhaps causing the upwelling mechanism to operate more energetically.

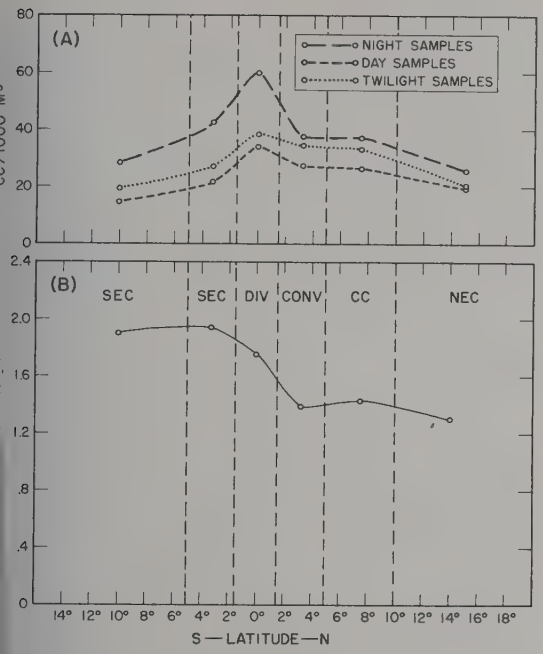
DIURNAL VARIATION AND THE CURRENT SYSTEM

Many physical and biotic conditions influence the vertical movement of planktonic animals (Kikuchi, 1930; Cushing, 1951). The diurnal variation which we have observed in the zooplankton catch from 200-meter oblique hauls probably results from a combination of factors which include: (1) vertical migration of the organisms in response to changes in illumination, and (2) their increased ability to dodge the net during daylight hours. In Hawaiian waters and in the central equatorial Pacific, night hauls yield catches about 1½ times the volume of day hauls (table 1). When the average volumes of night, day, and twilight hauls are segregated with respect to subdivisions of the current system, as in figure 16, we find a marked variation in the night/day ratio from north to south. In the North Equatorial Current, Countercurrent, and convergence zone the ratios range from 1.31 to 1.43, while in the divergent zone and the South Equatorial Current to the southward the ratios are much higher, ranging from 1.76 to 1.94. This trend appears consistently in the individual cruises.

The North Equatorial Current, an area of relatively shallow thermocline within the latitudes considered (fig. 7), has a very low night/day ratio; the convergent zone, with a deep thermocline, also has a low ratio, while the South Equatorial Current south of 5° S. latitude, which is an area

[8] In unpublished manuscript entitled, Review of Central Equatorial Pacific Oceanography, 1950–52.

[9] A study of the records had shown that a period of "doldrums" or northeast winds bring heavy rains to the northern Line Islands.



GURE 16.—Variations with the current system in (A) average volumes of night, day, and twilight hauls and in (B) the ratio of night to day zooplankton volumes.

moderate to deep thermocline, has a high ratio. e must conclude, therefore, that neither thermo- ne depth in itself nor the night/day ratio appears be related to the general level of zooplankton undance. Both high and low ratios are found areas of poor zooplankton catch. We must ve this problem for the present without an planation.

SHORT-TERM VARIATIONS

Two cruises of the *Hugh M. Smith* (cruise 11 d 15) crossing the equatorial currents on 150° d 140° W. longitude provide information on nporal changes in zooplankton volume and tribution as related to changes in the physical vironment.

On cruise 11 in August–October 1951, the north- nd leg (stations 28–50) was worked immedi- ly after the southbound leg (stations 1–28). ring the time interval (approximately 6 days) ween crossings of the Equator, the wind (SE.) reased from about 20 knots to about 12 knots. Indicated by the change in positions of the 80° F. herm (fig. 17), the zone of mixing at the Equator, i. e., the zone of cool, newly upwelled water, shifted to the south and narrowed in width during the 6-day interval. On the first leg the zooplankton maximum occurred at 1° N. latitude; on the second leg it occurred at 0° with a second peak of almost equal abundance at 2° S. latitude. These changes would seem to be evidence that during this 6-day period there was a shift in zooplankton distribution correlated with changes in zonal flow.

In the region of the Countercurrent during cruise 11, there was little change in winds within the interval (about 32 days) between sections, but there was a marked increase in rate of flow, as indicated by the broadening of the Countercurrent and steepening of the thermocline. These changes in the current were accompanied by a significant change in the zooplankton distribution (fig. 17). At the time of the first crossing there was little variation among stations within the Countercurrent; at the second crossing, following an increase in the current velocity from 45 to 80 cm./sec., there was a marked gradient in zooplankton concentration with the larger volumes being taken in the area of shallow thermocline at the northern boundary of the Countercurrent.

Additional information on time changes in the environment and the distribution of zooplankton along a particular meridian was obtained during May 1953 on *Hugh M. Smith* cruise 15 when 4 consecutive hydrographic and plankton sections were completed along 140° W. longitude with sampling from 9° N. to 7° S. latitude. The time

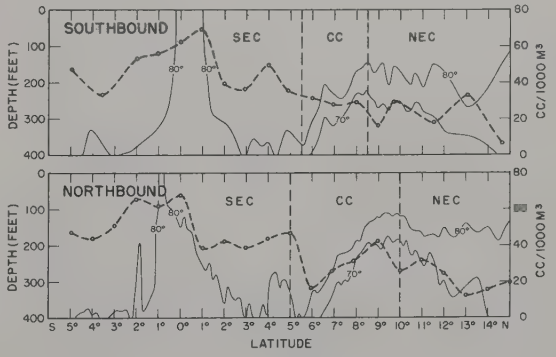


FIGURE 17.—South and northbound sections of *Hugh M. Smith* cruise 11 in August–October 1951, showing associated changes in zooplankton distribution (adjusted volumes) and temperature along 150° W. longitude. [Temperature sections adapted from Austin 1954a.]

interval between the first and fourth crossings of the Equator was 16 days and from the start of section 1 to the end of section 4 was 23 days. Austin (1954b) summarizes the hydrographic changes during this period as follows:

1. The slope of the isotherms associated with the Countercurrent is greater in the fourth than in the first leg, suggesting an increased easterly flow of the Countercurrent. This was substantiated in the calculated velocities, 60 cm./sec. on the first leg and 120 cm./sec. on the fourth leg.

2. The 80° isotherm-surface intercepts for the fourth section have moved to the north and south of those for the first section.

3. The 70° isotherm shows considerably more doming at the Equator in the fourth section.

4. Between the first and fourth sections there is a generally southerly shift in selected isohalines. There is a similar change in the slope of sigma-t isopleths in the region of the Countercurrent. Selected sigma-t surfaces show a general displacement to the south when comparing the first and fourth sections.

5. The most apparent change in the phosphate sections is the deepening of the 0.8 and 2.0 μg at/L isopleths in the region of the Countercurrent which is associated with the suggested change in flow, and the change in configuration of the 0.8 μg at/L isopleth near to and south of the Equator.

Observations of wind speed and velocity along the four section lines, as diagramed by Austin

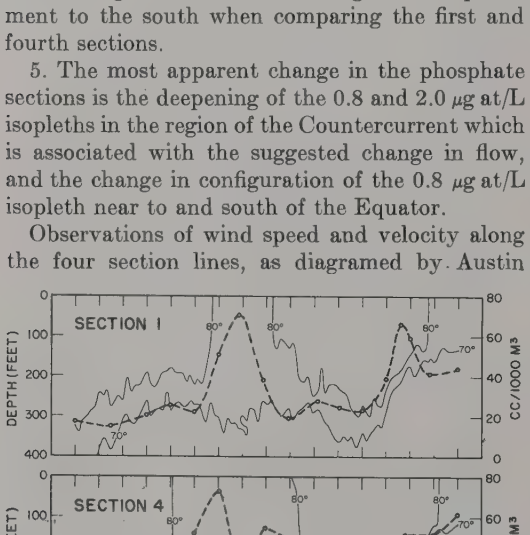


FIGURE 18.—Variation in (adjusted) zooplankton volumes and in the configuration of the 70° and 80° F. isotherms on sections 1 and 4 of *Hugh M. Smith* cruise 15, along 140° W. longitude in May–June 1952. [Temperature sections adapted from Austin 1954b.]

(1954b), show this was a period of moderate and variable winds. Since we did not have observations simultaneously to the north and south of the section lines, the changes with time are complex and difficult to summarize. In the region of the Countercurrent there appears to have been a reduction in the northeast trade winds and an extension to the northward of the moderate southeast trades. South of the Equator there was first a slackening in the winds followed by an increase with the strongest winds of the cruise being recorded on the southern ends of the third and fourth sections.

When the adjusted zooplankton volumes (table 9, appendix B) from the four series of stations along 140° W. are subjected to an analysis of variance with two-way classification, we find there are no significant ($P>0.05$) differences among the four sections but highly significant ($P<0.01$) differences among stations (latitudes). The latter significance results from the wide difference between the high volumes obtained in the Countercurrent and at the Equator and the low volumes from about 3° S. to 7° S. latitude.

When we examine differences in zooplankton distribution between the first and fourth legs in relation to changes in the temperature structure at the Equator (fig. 18), we find that the increased distance between the 80° isotherm-surface intercepts (an indication of an increase in width of the mixing zone) was accompanied by a broadening of the zooplankton "rich zone." On the first section there was a single peak of abundance directly on the Equator; on the fourth section there were two peaks, at about 1° S. and 1° N latitude, with a trough at the Equator. In the Countercurrent the zooplankton catch was high in volume on all four sections. The suggested change in rate of flow in the Countercurrent was not reflected in any noticeable change in zooplankton abundance or distribution.

It is difficult to explain or to draw conclusions from these events. In one instance (cruise 11) a change in rate of flow of the Countercurrent was accompanied by a change in zooplankton distribution; in the second instance (cruise 15) changes in the Countercurrent were not evidenced by any noticeable change in the volume of zooplankton. On both cruises an increase in breadth of the zone of divergence or mixing at the Equator was followed by a corresponding broadening in the plan

ton rich zone. It does not seem likely that these rather quick responses of zooplankton to variations in the physical environment are the result of immediate changes in biological productivity reflected in growth of the population, but are simply a shifting and perhaps dispersal or concentration of the population associated with changes in the water mass.

PHOSPHATE, ZOOPLANKTON, AND TUNA

The primary objective of our zooplankton studies has been to obtain an estimate of the basic fish food present in different areas of the sea with the hope that this information would increase our understanding of variations in the abundance and distribution of the tunas. Where other factors, temperature for example, are not of a limiting nature, fast-swimming oceanic fishes such as the tunas will occur, we believe, in proportion to the amount of substance available for their nutriment. This does not mean that we expect to find a high positive correlation at all times and places between the volume of food and the abundance of tunas. In fact, it is probable that an inverse relation may exist locally after a period of intensive feeding. In general, however, when broad areas of the sea are being compared, we believe that high abundance of fish is most likely to occur in areas of high concentration of zooplankton and other forage organisms.

The distribution of yellowfin tuna, *Neothunnus macropterus* (Temminck and Schlegel), summarized in figure 19, is derived from 12 cruises in the central equatorial Pacific during the years 1950–53.[10] The highest average catch (5.3 yellowfin per 100 hooks) was obtained in the convergent zone, with the second highest catch in the region of the divergence. Although the peaks in abundance do not exactly coincide, it is obvious that there is more than a casual relation between zooplankton and yellowfin. The best catches of bigeye, *Parathunnus sibi* (Temminck and Schlegel), were made in the North Equatorial Current and Countercurrent (fig. 19). This species appears to respond in a different manner than the yellowfin to the better foraging conditions in the convergent and divergent zones. A comparative study of the food of the two species failed to show differences in the

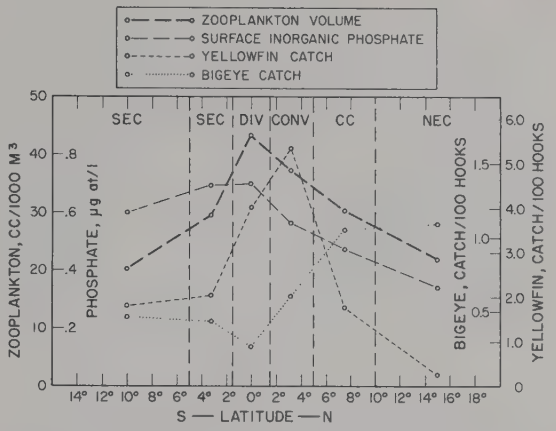


FIGURE 19.—Variations with the current system in yellowfin and bigeye catch on longline gear, zooplankton volumes (adjusted) and surface inorganic phosphate, for the range of longitude 120° W. to 180°. The tuna catch data are derived from cruises 7, 11, and 18 of the *Hugh M. Smith*, cruises 11, 12, 13, 14, 15, 16, and 18 of the *John R. Manning*, cruise 1 of the *Charles H. Gilbert*, and cruise 1 of the *Cavalieri*. The phosphate data are from cruises 2, 5, 8, 11, 14, 15, 16, 18, and 19 of the *Hugh M. Smith*.

diet which might explain this marked difference in distribution (King and Ikehara, 1956).

Measurements of inorganic phosphate performed on POFI hydrographic cruises during the years 1950–53 show that the zone of divergence and the South Equatorial Current immediately south of the Equator contained the highest concentrations of this basic chemical nutrient while the North Equatorial Current contained the lowest (fig. 19). This variation may result from unequal utilization of phosphate and/or the unequal mixing of high and low phosphate water to the north and south of the Equator as the result of the asymmetrical effects of the southeast winds. As evidenced by the zooplankton and yellowfin catch, the greatest organic productivity occurred on, or to the north of the Equator. The difference in degree of northward displacement for the two eutrophic levels, zooplankton and tuna, may to some extent be indications of the lag periods in their development and may also be related to the slow northward drift in the surface currents under the influence of east and southeast winds.

When long series of stations extending in a north-south direction are examined, we usually find a highly significant positive correlation be-

[10] The tuna catch records employed in this report have resulted from exploratory longline fishing conducted by POFI vessels and are analyzed in other POFI reports (Murphy and Shomura 1953a, 1953b, 1955; Shomura and Murphy 1955; Iversen and Yoshida, 1956.

TABLE 5.—*Correlations of adjusted zooplankton volumes (cc./1000 m.³) as the X_1 variate, with X_2 variate the surface inorganic phosphate or yellowfin longline catch from same locality*

X_2 variate	Motor vessel and cruise No.	Range of latitude	Degrees of freedom	Correlation coeffi-cient(r)	P
Inorganic phosphate, μg at/L	Hugh M. Smith—2	24° N.–5° S.	22	0.771	<0.01
Inorganic phosphate, μg at/L	Hugh M. Smith—5	27° N.–5° S.	41	0.678	<0.01
Inorganic phosphate, μg at/L	Hugh M. Smith—8	21° N.–14° S.	50	0.365	<0.01
Inorganic phosphate, μg at/L	Hugh M. Smith—11	19° N.–4° S.	20	0.631	<0.01
Yellowfin catch per 100 hooks	Hugh M. Smith—11	15° N.–5° S.	25	0.381	0.05
Inorganic phosphate, μg at/L	Hugh M. Smith—14	9° N.–8° S.	34	0.277	>0.05
Yellowfin catch per 100 hooks [1]	John R. Manning—11	8° N.–8° S.	24	0.286	>0.05
Inorganic phosphate, μg at/L	Hugh M. Smith—15	9° N.–7° S.	58	−0.294	<0.05
Inorganic phosphate, μg at/L	Hugh M. Smith—18	9° N.–9° S.	16	0.101	>0.05
Yellowfin catch per 100 hooks	Hugh M. Smith—18	9° N.–9° S.	22	−0.177	>0.05

[1] In this instance zooplankton volumes obtained by *Hugh M. Smith* cruise 14 were correlated with longline catches of *John R. Manning* cruise 11, the two cruises occurring during the same period of time.

tween surface inorganic phosphate and zooplankton volumes (table 5). With a short series of stations the correlation may be nonsignificant as that for the *Hugh M. Smith* cruises 14 and 18, or even be significantly negative as for cruise 15. The latter is perhaps an example of an inverse relation resulting from high utilization. The correlation of zooplankton volume and yellowfin catch was significant (P=0.05) for *Hugh M. Smith* cruise 11, but non-significant for cruise 11 of the *John R. Manning* and cruise 18 of the *Hugh M. Smith*.

Within the equatorial "rich zone," from the southern boundary of the Countercurrent at about 5° N. latitude to 5° S. latitude, zooplankton and yellowfin showed a gradient of increasing abundance between 180° and 150° W. (fig. 20). The yellowfin catch continued high at 140° W. and then dropped off sharply to the east, while zooplankton volume varied somewhat irregularly to the east but remained moderately high. The variation in surface inorganic phosphate was roughly just the reverse (fig. 20), with high concentrations on the eastern and westernmost longitudes and low values in between. We have no empirical explanation at present for this distribution of phosphate. It may possibly result from differences in rate of utilization as the most productive areas appear to be the mid-longitudes.

In the equatorial region of the central Pacific, July, August, and September was the period of best yellowfin catch (fig. 21). It was also the period of highest zooplankton abundance, although the quarter October, November, and December was essentially of equal rank. Phos-

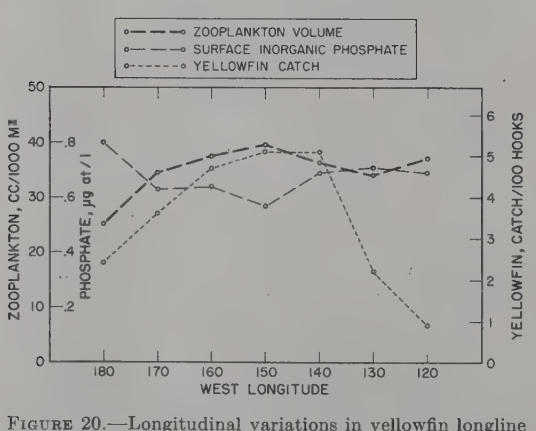


FIGURE 20.—Longitudinal variations in yellowfin longline catch, zooplankton volumes (adjusted) and surface inorganic phosphate for the South Equatorial Current from the southern boundary of the Countercurrent, at about 5° N. latitude to 5° S. latitude, with the data segregated by 10-degree intervals of longitude.

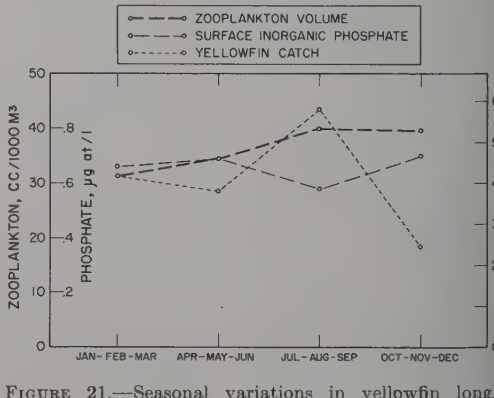


FIGURE 21.—Seasonal variations in yellowfin longline catch, zooplankton volumes (adjusted) and surface inorganic phosphate for the South Equatorial Current from the southern boundary of the Countercurrent at about 5° N. latitude to 5° S. latitude, with the data segregated into quarterly periods of 3 months each.

phate again showed an inverse correlation, particularly with the yellowfin catch. Figure 14B demonstrates the difference in yellowfin catch for the two 6-month periods: (1) January–June, a period of generally light, variable or northeast winds, and (2) July–December, a period of strong southeast trades. With the change in winds during the latter half of the year there was apparently a shift to the northward in the area of best catch. The zooplankton exhibited a general increase during this period, especially in the convergent zone.

SUMMARY AND CONCLUSIONS

1. This is the second report of the Pacific Oceanic Fishery Investigations on variations in zooplankton abundance in the central Pacific; it presents the results of 270 quantitative hauls made on eight cruises during the years 1951 to 1954. Data from earlier cruises, included in a previous report (King and Demond, 1953), were also utilized in this study.

2. The majority of the collections were obtained with 1-meter nets of 30XXX grit gauze (aperture widths 0.65 mm.). For comparison, a few hauls were made with 56XXX nets (aperture widths 0.31 mm.). Oblique hauls to 200 meters' depth were employed at most stations. The results from a short series of horizontal hauls are included.

3. The displacement volumes of all samples were measured in the laboratory. For each sample there was calculated the volume of the more nutritious zooplankton per unit of water strained. Counts were made on six samples to examine the composition of the catch from nets of different mesh size.

4. The catch of 56XXX grit gauze nets (aperture widths 0.31 mm.) was about 1¼ to 1¾ times greater in volume than that of the catch of the 30XXX nets (aperture widths 0.65 mm.). The number of plankters retained by the finer-meshed net was 3 to 5 times that retained by the coarser-meshed net. At three stations, two rich and one poor, the catches for the two nets were generally proportional.

5. Horizontal hauls made simultaneously at three levels showed that the greatest bulk of zooplankton was near the surface even in the daytime, rather than at depths just above or below the thermocline.

6. The night hauls yielded volumes averaging 1.57 times the volumes of day hauls; twilight hauls were intermediate in volume. To reduce these differences associated with hour of hauling, a method of adjustment was employed based upon the similarity between the diurnal variation in zooplankton abundance in the upper 200 meters and the curve of the sine function, with midnight equated to the angle whose sine is +1.0.

7. When the adjusted zooplankton volumes were combined according to natural subdivisions of the equatorial current system, disregarding differences associated with longitude and season, we found the greatest concentration of zooplankton occurring at the Equator in the region of upwelling and divergence. Average volumes for the convergent zone and the Countercurrent were greater than for the South Equatorial Current south of the Equator. This asymmetrical distribution of zooplankton in respect to the Equator may result from the prevalence of southeast trade winds in this part of the Pacific.

8. As determined from exploratory longline fishing conducted by POFI, in the central equatorial Pacific the greatest abundance of yellowfin tuna occurred in the convergent zone just to the north of the area of highest zooplankton abundance, and although the peaks did not exactly coincide, there was a high degree of co-variation in yellowfin and zooplankton in respect to the current system.

9. Oceangraphic fronts occurring in the transition zone between the Equator and the southern boundary of the Countercurrent appeared to demarcate areas of high zooplankton abundance on the south from areas of poor to moderate abundance on the north.

10. The Countercurrent in the east-central Pacific produced unusually high zooplankton volumes. As this is an area of shallow thermocline, with high-phosphate water within the photosynthetic zone and within reach of wind-induced turbulence, conditions are more favorable for plankton production than farther to the westward where the thermocline deepens.

11. Within the equatorial region there was a west-east gradient of increasing zooplankton abundance from 180° to 150° W. longitude which was correlated positively with average wind velocity and inversely with thermocline depth, and was closely paralleled by a gradient of increasing yellowfin catch. East of 140° W. the yellowfin catch

dropped sharply, but zooplankton volumes remained high.

12. Largest zooplankton volumes occurred in the quarter, July, August, and September, with October, November, and December essentially equal in rank, and the lowest in January, February, and March. Best yellowfin catches were obtained in July, August, and September.

13. Zooplankton volumes averaged considerably higher in the year 1950 than in 1951, 1952, and 1953. There was some indication of a rising trend in 1954.

14. The ratio of the volumes of night hauls to day hauls ranged from 1.31 to 1.43 in divisions of the current system north of the Equator, and from 1.76 to 1.94 at the Equator and in the South Equatorial Current to the southward. The night/day ratio did not appear to be related to thermocline depth or to general level of plankton abundance.

15. With an increase in breadth of the mixing zone associated with the divergence at the Equator, there was a corresponding broadening in the zooplankton rich zone. On one cruise an increase in rate of flow of the Countercurrent was accompanied by a marked change in the distribution of zooplankton within the current. These observations indicate that the zooplankton was quick to respond to physical changes in the environment by dispersal or concentration of the population following changes in the water mass.

16. On long series of stations extending from the phosphate-poor North Equatorial Current to south of the Equator, we found highly significant positive correlations between zooplankton volume and surface inorganic phosphate. On series covering a short range of latitude the correlation was insignificant or even negative.

Although the highest concentration of phosphate occurred in the divergent zone at the Equator, agreeing in this respect with zooplankton, longitudinally and seasonally there was some evidence of an inverse relationship with zooplankton and yellowfin; this may result from differences in rate of utilization.

17. Zooplankton distribution was rather uniform throughout the island waters of Palmyra, an atoll lying in the Countercurrent at about 162° W. longitude. Sampling along four station lines extending from a few hundred yards from the outer reef to about 14 miles offshore revealed no significant change in zooplankton abundance with distance from land (appendix A).

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APPENDIX A

ZOOPLANKTON DISTRIBUTION ABOUT AN OCEANIC ISLAND

Palmyra Island lies 352 nautical miles north of the Equator and about a thousand miles south of Honolulu. In relation to other islands of the Line Islands group, Palmyra is located about 33 miles southeast of Kingman Reef and 120 miles northwest of Washington Island. The island is an atoll consisting of 40 to 50 small islets arranged in a rectangle about 4 miles long and 1½ miles wide. The islets rest on a shallow reef platform 6 miles long and 2 miles wide with the long axis of the platform extending in an east-west direction. Outside the 10-fathom line the submarine slope is steep, ranging from 2,500 to 3,000 feet to the mile and descending to the general depth of about 15,000 feet (Wentworth 1931).

Occupying latitudes 5°52′ N. to 5°54′ N. at approximately 162° W. longitude, Palmyra lies close to the southern boundary of the Countercurrent and ordinarily is bathed by it throughout the year. The surface current was flowing to the east at the time of our observations, as was to be expected, since, in the region of the Line Islands, the southern boundary of the Countercurrent has always occurred south of 5½° N. latitude on the numerous crossings of POFI vessels.

The zooplankton abundance about the island was investigated in January 1953, on *Hugh M. Smith* cruise 19, by running lines of stations out to the north, south, east, and west, starting as close to the reef as the vessel's safety permitted and extending out to a maximum of about 14 miles (fig. 3). A total of 20 hauls were made, all at night. With the exception of a single haul made on the shallow shelf west of the island which yielded a sample about twice the average volume of the 200-meter oblique tows, the results indicated a rather uniform distribution of zooplankton throughout the island waters.[11] From an analysis of variance we conclude that the differences between the four series of stations were not significant ($F=0.896$, $P>0.05$). There was a slight indication of an inverse relation between the zooplankton catch and distance from land (fig. 22); a regression analysis showed, however, that this trend was not significantly different ($b=-0.431$, $P>0.1$) from a random distribution.

The variation about Palmyra was less than was found in two series of stations extending offshore from Oahu, Hawaii. Here the largest volumes occurred at one or two miles from shore and the difference between stations was significant (King and Hida, 1954). Although the sampling was entirely inadequate for any broad conclusions, it appears evident that at the time of our visit to Palmyra there was no definite gradient in zooplankton abundance along four station lines extending from a few hundred yards from the outer reef to about 14 miles offshore.

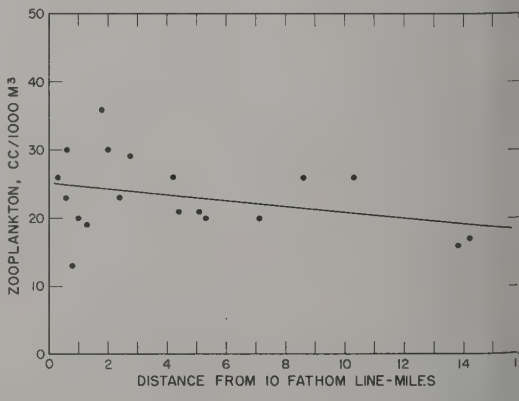

FIGURE 22.—Zooplankton volumes (adjusted) in relation to distance offshore from the 10-fathom line, Palmyra Island, January 1953, *Hugh M. Smith* cruise 19.

[11] The salinity and temperature data collected on this cruise indicated that the waters about Palmyra were also rather uniform as to chemical and physical conditions; e. g., the maximum variation in surface temperature was less than 0.5° C.

APPENDIX B

TABLE 6.—*Zooplankton volumes obtained on cruise 9 of the* Hugh M. Smith, *with collection data*

Station No.	Position		Date	Time [1]	Water strained, m.[3]	Zooplankton, cc./1000 m.[3]	
	Latitude	Longitude				Sample volume	Adjusted volume [2]
Oblique tows, 200 m. depth; 1-meter nets, 30XXX grit gauze:							
1	25°40′ N.	175°24′ W.	May 21, 1951	1202–1235	3304.0	10.3	13.7
2	22°45′ N.	173°16′ W.	May 22, 1951	1210–1237	1932.5	15.7	20.9
3	19°33′ N.	171°32′ W.	May 23, 1951	1214–1238	1385.4	23.0	30.6
4	16°05′ N.	169°06′ W.	May 26, 1951	1224–1250	1312.7	18.0	23.9
5	13°15′ N.	166°45′ W.	May 27, 1951	1233–1301	[3] 1366.4	10.5	13.9
6	10°16′ N.	164°49′ W.	May 28, 1951	([4])			
7	7°27′ N.	163°05′ W.	May 29, 1951	1246–1316	1505.0	18.7	24.7
8	5°35′ N.	161°44′ W.	June 3, 1951	1545–1614	1480.8	35.0	40.4
9	4°23′ N.	160°02′ W.	June 5, 1951	1358–1430	1517.2	22.5	28.4
10	2°43′ N.	158°15′ W.	June 7, 1951	1203–1235	1656.3	29.5	39.3
11	1°28′ N.	158°02′ W.	June 10, 1951	1206–1243	3026.6	14.4	19.1
12	0°27′ S.	160°20′ W.	June 11, 1951	1200–1235	2531.3	21.2	28.2
13	1°31′ S.	164°05′ W.	June 12, 1951	1144–1216	2302.6	22.1	29.4
14	2°04′ S.	168°16′ W.	June 13, 1951	1224–1254	1930.0	19.4	25.8
15	3°05′ S.	172°07′ W.	June 17, 1951	1408–1438	1997.6	23.2	29.4
16	4°32′ S.	172°48′ W.	June 19, 1951	0804–0834	1647.5	24.3	28.7
17	4°28′ S.	171°38′ W.	June 20, 1951	1207–1240	1975.4	30.1	40.1
18	3°59′ S.	171°26′ W.	June 21, 1951	1209–1242	2336.1	25.1	33.4
19	0°32′ S.	170°33′ W.	June 24, 1951	1213–1243	2103.3	17.6	23.4
20	2°18′ N.	168°43′ W.	June 25, 1951	1222–1251	1994.2	15.7	20.8
21	5°12′ N.	166 46′ W.	June 26, 1951	1232–1304	2275.1	17.8	23.6
22	8°05′ N.	165°11′ W.	June 27, 1951	1233–1302	1978.8	25.2	33.4
23	11°24′ N.	163°37′ W.	June 28, 1951	1240–1307	1521.6	14.2	18.8
24	14°40′ N.	161°49′ W.	June 29, 1951	1250–1322	2371.7	8.2	10.8
25	17°40′ N.	159°57′ W.	June 30, 1951	1253–1324	2716.2	11.3	14.9
26	20°34′ N.	158°15′ W.	July 1, 1951	1200–1231	2622.3	17.5	23.1

[1] Apparent solar time.
[2] Adjusted for day-night difference by the sine transformation method ing a pooled regression coefficient (0.1248).
[3] Based on an estimated meter reading.
[4] No sample.

TABLE 7.—*Zooplankton volumes obtained on cruise 11 of the* Hugh M. Smith, *with collection data*

Station No.	Position		Date	Time [1]	Water strained, m.[3]	Zooplankton, cc./1000 m.[3]	
	Latitude	Longitude				Sample volume	Adjusted volume [2]
Oblique tows, 200 m. depth; 1-meter nets, 30XXX grit gauze:							
1	14°37′ N	150°12′ W	Aug. 24, 1951	0851-0922	1437.7	5.9	6.
2	13°06′ N	149°58′ W	Aug. 25, 1951	0826-0853	1223.7	29.2	33.
3	11°31′ N	150°02′ W	Aug. 26, 1951	0830-0902	1898.0	15.8	17.
4	9°41′ N	150°01′ W	Aug. 27, 1951	0759-0828	1363.2	26.3	29.
5	8°58′ N	150°08′ W	Aug. 28, 1951	0720-0754	1852.4	15.2	16.
6	7°59′ N	149°51′ W	Aug. 29, 1951	0754-0832	2838.5	26.2	29.
7	6°55′ N	149°51′ W	Aug. 30, 1951	0734-0805	1693.4	25.7	27.
8	5°59′ N	149°55′ W	Aug. 31, 1951	0742-0810	1540.6	28.8	31.
9	4°49′ N	150°02′ W	Sept. 1, 1951	0731-0804	1954.6	32.8	35.
10	4°00′ N	150°02′ W	Sept. 2, 1951	0739-0812	699.9	45.1	49.
11	2°55′ N	150°09′ W	Sept. 3, 1951	0738-0807	1699.8	33.0	36.
12	1°59′ N	150°04′ W	Sept. 4, 1951	0741-0811	1935.4	36.0	39.
13	2°02′ N	151°39′ W	Sept. 5, 1951	0729-0800	1034.0	28.2	30.
14	2°03′ N	153°05′ W	Sept. 6, 1951	0729-0758	1458.4	35.5	38.
15	1°53′ N	155°18′ W	Sept. 12, 1951	0729-0759	1773.6	46.9	50.
16	2°02′ N	156°13′ W	Sept. 13, 1951	0718-0749	1752.6	33.8	36.
17	1°58′ N	157°32′ W	Sept. 14, 1951	0713-0746	1683.2	26.6	28.
18	1°21′ N	157°18′ W	Sept. 15, 1951	0731-0803	1827.2	26.7	29.
19	1°54′ N	156°15′ W	Sept. 16, 1951	0725-0753	1358.8	34.3	37.
20	2°02′ N	154°43′ W	Sept. 17, 1951	0733-0803	1455.1	34.1	37.
21	2°03′ N	153°04′ W	Sept. 18, 1951	0742-0813	1492.3	55.8	61.
22	2°00′ N	151°18′ W	Sept. 19, 1951	0744-0812	1294.5	52.0	57.
23	0°55′ N	149°54′ W	Sept. 20, 1951	0748-0818	1311.3	63.1	69.
24	0°01′ S	149°56′ W	Sept. 21, 1951	0750-0820	1471.2	56.7	62.
25	1°03′ S	150°16′ W	Sept. 22, 1951	0752-0808	1133.4	51.3	56.
26	2°01′ S	150°08′ W	Sept. 23, 1951	0743-0813	1187.4	48.8	53.
27	3°34′ S	150°05′ W	Sept. 24, 1951	0748-0820	1546.0	30.1	33.
28	4°57′ S	150°04′ W	Sept. 25, 1951	0914-0944	1337.3	41.1	47.
29	4°00′ S	150°00′ W	Sept. 26, 1951	0000-0033	1882.7	53.4	44.
30	3°00′ S	149°57′ W	do	0906-0937	1635.0	44.3	51.
31	2°00′ S	150°02′ W	do	1728-1758	1389.5	65.0	66.
32	1°00′ S	149°58′ W	Sept. 27, 1951	0219-0249	1505.7	71.9	62.
33	0°02′ N	150°00′ W	do	1309-1338	1124.0	56.7	68.
34	1°02′ N	150°01′ W	do	2341-0011	1569.9	47.2	38.
35	2°01′ N	149°53′ W	Sept. 28, 1951	0849-0920	1544.3	36.9	42.
36	3°00′ N	150°03′ W	do	1724-1755	1628.2	38.2	38.
37	3°58′ N	150°00′ W	Sept. 29, 1951	0201-0231	1531.2	51.8	44.
38	4°59′ N	149°56′ W	do	1048-1119	1072.2	38.9	46.
39	5°56′ N	150°00′ W	do	1929-2000	1660.0	18.3	16.
40	6°51′ N	149°57′ W	Sept. 30, 1951	0353-0423	1632.2	28.7	26.
41	7°51′ N	149°57′ W	do	1307-1338	1932.1	26.2	31.
42	8°57′ N	149°58′ W	do	2243-2312	1465.9	51.0	42.
43	10°00′ N	150°13′ W	Oct. 1, 1951	0718-0749	1790.3	24.0	26.
44	10°58′ N	150°02′ W	do	1604-1634	1733.7	29.5	32.
45	11°59′ N	150°03′ W	Oct. 2, 1951	0052-0123	1471.2	29.8	24.
46	13°00′ N	149°56′ W	do	0918-0948	1596.4	10.8	12.
47	14°01′ N	150°03′ W	do	1744-1815	1782.5	15.7	15.
48	15°02′ N	150°01′ W	Oct. 3, 1951	0155-0226	1596.4	23.2	19.
49	17°00′ N	150°42′ W	do	1701-1733	1942.7	13.7	14.
50	19°00′ N	151°19′ W	Oct. 4, 1951	0756-0826	1965.3	12.3	13.

[1] Apparent solar time. [2] Adjusted for day-night difference by the sine transformation method.

TABLE 8A.—*Zooplankton volumes obtained on cruise 14 of the* Hugh M. Smith, *and collection data*

Station No.	Position		Date	Time[1]	Water strained, $m.^3$	Zooplankton, cc./1000 $m.^3$	
	Latitude	Longitude				Sample volume	Adjusted volume[2]
A. Oblique hauls to 200 m. depth; 1-meter nets, 30XXX grit gauze:							
1	7°57′ N	154°57′ W	Jan. 27, 1952	1125–1151	1014.4	23.5	31.9
2	6°55′ N	154°57′ W	do	2059–2129	1334.6	43.2	34.1
3	5°53′ N	154°55′ W	Jan. 28, 1952	0740–0810	1128.6	10.1	11.8
4	4°55′ N	154°51′ W	do	1635–1711	1533.9	22.6	24.5
5	3°54′ N	154°51′ W	Jan. 29, 1952	0135.0205	1325.4	28.0	21.4
6	2°56′ N	154°59′ W	do	1024–1054	1033.8	24.5	32.7
7	1°54′ N	155°03′ W	do	1937–2008	1150.5	27.6	23.7
8	0°54′ N	155°11′ W	Jan. 30, 1952	0803–0836	1330.0	8.4	10.0
9	0°06′ S	155°14′ W	do	1831–1915	2054.2	35.1	32.4
10	1°10′ S	155°08′ W	Jan. 31, 1952	0418–0457	1647.3	42.7	38.4
11	2°00′ S	155°03′ W	do	1127–1159	1479.6	22.7	30.8
12	3°00′ S	154°58′ W	do	2051–2122	1511.2	26.3	21.1
13	4°00′ S	155°07′ W	Feb. 1, 1952	0633–0709	1394.6	16.5	17.9
14	4°58′ S	155°00′ W	do	1846–1918	1246.3	25.0	23.1
15	5°53′ S	155°03′ W	Feb. 2, 1952	0421–0458	1334.6	27.8	25.0
16	6°50′ S	155°05′ W	do	1333–1402	1316.0	13.3	17.6
17	7°56′ S	179°53′ W	Feb. 15, 1952	0102–0137	1878.2	9.6	7.2
18	7°01′ S	179°49′ W	do	1040–1110	1670.5	15.0	20.2
19	6°05′ S	179°58′ W	do	1946–2016	1546.1	17.3	14.8
20	5°04′ S	179°58′ W	Feb. 16, 1952	0515–0550	1755.6	19.9	19.4
21	4°03′ S	179°58′ W	do	1452–1522	1307.1	23.0	28.6
22	2°56′ S	180°00′ W	Feb. 17, 1952	0026–0057	1389.7	31.4	23.2
23	1°52′ S	180°06′ W	do	1053–1122	1342.1	15.0	20.2
24	0°59′ S	180°03′ W	do	1918–1951	1642.0	34.1	29.9
25	0°02′ N	180°01′ W	Feb. 18, 1952	0506–0539	1214.6	31.7	30.1
26	1°03′ N	179°58′ W	do	1601–1637	1505.8	23.6	26.9
27	2°07′ N	179°57′ W	Feb. 19, 1952	0156–0227	1067.7	35.4	27.5
28	3°06′ N	179°57′ W	do	1051–1124	1738.6	10.1	13.6
29	4°05′ N	179°55′ W	do	1954–2025	1472.9	35.4	30.3
30	5°06′ N	179°50′ W	Feb. 20, 1952	0452–0525	1699.5	23.8	22.0
31	6°06′ N	179°44′ W	do	1358–1428	1451.3	16.9	21.8
32	7°04′ N	180°01′ W	do	2254–2326	1605.2	20.9	15.4
33	8°03′ N	179°58′ W	Feb. 21, 1952	0745–0814	1296.3	20.1	23.4
34	8°58′ N	179°55′ W	do	1707–1737	1329.9	16.1	17.0
35	4°59′ S	168°59′ W	Mar. 1, 1952	1705–1737	1779.1	11.9	12.6
36	4°03′ S	168°58′ W	Mar. 2, 1952	0155–0224	1506.7	26.9	20.6
37	3°04′ S	168°59′ W	do	1131–1202	1158.3	10.7	14.5
38	2°04′ S	168°57′ W	do	2211–2241	1028.6	19.5	14.8
39	1°03′ S	168°54′ W	Mar. 3, 1952	0805–0833	994.1	24.6	29.4
40	0°02′ S	169°00′ W	do	1800–1831	1228.4	41.6	40.5
41	1°03′ N	169°00′ W	Mar. 4, 1952	0354–0426	1176.7	61.5	54.0
42	2°05′ N	168°57′ W	do	1544–1613	946.0	28.8	33.6
43	3°04′ N	169°00′ W	Mar. 5, 1952	0116–0147	1150.5	43.2	32.7
44	4°05′ N	168°57′ W	do	1025–1050	828.5	22.5	30.1
45	4°57′ N	168°56′ W	do	1910–1936	1091.4	12.3	11.1
46	5°56′ N	169°00′ W	Mar. 6, 1952	0416–0449	1583.8	31.5	28.3
47	6°57′ N	168°54′ W	do	1742–1811	1455.4	21.6	21.6

[1] Apparent solar time. [2] Adjusted for day-night difference by the sine transformation method.

TABLE 8B.—*Zooplankton volumes obtained on cruise 14 of the* Hugh M. Smith, *with collection data*

Special station	Sample	Position		Date	Time[1]	Estimated depth of haul, m.	Water strained, $m.^3$	Sample volume cc./1000 $m.^3$
		Latitude	Longitude					
Horizontal hauls at various depths:								
S1	1	2°41′ S	171°44′ W	Feb. 9, 1952	1315–1443	210	2694.6	15.4
	2	2°41′ S	171°44′ W	do	1322–1438	105	2594.1	23.9
	3	2°41′ S	171°44′ W	do	1329–1429	0	2591.9	32.2
S2	1	2°41′ S	171°44′ W	do	1557–1724	210	3378.0	22.6
	2	2°41′ S	171°44′ W	do	1603–1719	105	2508.1	30.1
	3	2°41′ S	171°44′ W	do	1610–1711	0	2504.2	47.8
S3	1	2°43′ S	171°43′ W	do	1848–2021	210	1433.7	29.2
	2	2°43′ S	171°43′ W	do	1856–2012	105	1309.3	33.7
	3	2°43′ S	171°43′ W	do	1903–2004	0	2317.2	45.5
S4	1	2°44′ S	171°45′ W	do	2034–2205	240	1835.5	22.4
	2	2°44′ S	171°45′ W	do	2042–2159	120	2472.1	23.2
	3	2°44′ S	171°45′ W	do	2050–2151	0	2302.8	49.2
S5	1	2°45′ S	171°43′ W	do	2221–2355	240	1378.6	25.4
	2	2°45′ S	171°43′ W	do	2232–2347	120	1843.1	23.6
	3	2°45′ S	171°43′ W	do	2242–2341	0	2332.7	[2] 157.8
S6	1	2°41′ S	171°43′ W	Feb. 10, 1952	0029–0157	220	1448.6	27.8
	2	2°41′ S	171°43′ W	do	0036–0149	110	2175.2	26.9
	3	2°41′ S	171°43′ W	do	0043–0142	0	2616.5	44.1
S7	1	2°41′ S	171°43′ W	do	0225–0354	240	1118.1	41.8
	2	2°41′ S	171°43′ W	do	0230–0345	120	1137.2	39.3
	3	2°41′ S	171°43′ W	do	0238–0338	0	2464.7	44.2

[1] Apparent solar time. [2] Estimated 50 percent amphipods.

TABLE 9.—*Zooplankton volumes obtained on cruise 15 of the* Hugh M. Smith, *with collection data*

Station No.	Position		Date	Time [1]	Water strained, $m.^3$	Zooplankton, cc./1000 $m.^3$	
	Latitude	Longitude				Sample volume	Adjusted volume [2]
Oblique tows, 200 m. depth; 1-meter nets, 30XXX grit gauze:							
1	8°59′ N.	139°56′ W.	May 28, 1952	0714–0745	1,421.8	40.1	44.
2	7°51′ N.	139°46′ W.	do.	1822–1855	1,617.5	43.7	41.
3	7°00′ N.	140°00′ W.	May 29, 1952	0258–0328	1,731.8	70.7	59.
4	6°36′ N.	139°44′ W.	do.	1018–1049	1,868.8	51.4	66.
5	6°00′ N.	140°00′ W.	do.	1710–1743	2,059.1	37.4	39.
6	5°02′ N.	139°58′ W.	May 30, 1952	0151–0223	1,896.4	42.4	33.
7	4°05′ N.	139°58′ W.	do.	0946–1016	2,167.6	27.4	34.
8	3°09′ N.	139°53′ W.	do.	1821–1853	1,510.8	29.4	28.
9	1°57′ N.	140°03′ W.	May 31, 1952	0326–0401	2,465.2	22.5	19.
10	0°53′ N.	140°02′ W.	do.	1219–1249	1,702.0	29.5	38.
11	0°11′ S.	139°52′ W.	do.	2121–2151	2,060.9	[3] 88.0	70.
12	1°02′ S.	139°52′ W.	June 1, 1952	0458–0530	1,947.7	53.8	51.
13	2°00′ S.	139°50′ W.	do.	1240–1311	1,572.7	17.1	22.
14	3°00′ S.	139°52′ W.	do.	2009–2040	1,523.7	30.0	25
15	4°00′ S.	140°05′ W.	June 2, 1952	0610–0640	1,323.8	20.2	20.
16	5°30′ S.	139°57′ W.	do.	1821–1851	1,361.6	16.0	15.
17	7°00′ S.	139°58′ W.	June 3, 1952	0651–0722	1,716.5	16.5	17.
18	5°26′ S.	140°00′ W.	do.	1928–1958	1,350.5	14.1	12.
19	3°52′ S.	140°04′ W.	June 4, 1952	0659–0730	1,793.9	23.1	25.
20	2°50′ S.	140°06′ W.	do.	1454–1529	1,849.9	25.3	30.
21	1°46′ S.	140°09′ W.	do.	2225–2250	1,326.1	38.0	29.
22	0°43′ S.	140°11′ W.	June 5, 1952	0644–0713	1,321.5	33.0	35.
23	0°00′	139°59′ W.	do.	1315–1345	1,250.6	23.3	29.
24	1°02′ N.	139°58′ W.	do.	2240–2308	1,377.5	44.7	34.
25	2°04′ N.	139°57′ W.	June 6, 1952	0805–0832	1,251.3	23.2	27.
26	3°06′ N.	140°00′ W.	do.	1701–1733	1,391.4	39.0	40.
27	4°09′ N.	140°06′ W.	June 7, 1952	0214–0254	1,948.1	48.8	39.
28	5°10′ N.	140°12′ W.	do.	1116–1147	1,438.7	44.8	58.
29	6°07′ N.	140°11′ W.	do.	1848–1920	1,569.8	58.7	54.
30	7°04′ N.	140°10′ W.	June 8, 1952	0334–0407	1,758.9	[4] 88.6	77.
31	8°00′ N.	140°00′ W.	do.	1043–1112	1,396.0	57.5	75.
32	7°04′ N.	140°04′ W.	do.	1859–1929	1,441.8	70.4	64.
33	6°05′ N.	139°58′ W.	June 9, 1952	0541–0614	1,978.1	46.8	46.
34	5°00′ N.	139°51′ W.	do.	1605–1641	1,856.1	22.2	24.
35	4°01′ N.	139°55′ W.	June 10, 1952	0107–0137	1,493.2	27.1	21.
36	3°00′ N.	139°57′ W.	do.	0927–0954	1,874.0	48.3	60.
37	2°00′ N.	139°56′ W.	do.	1757–1828	1,773.8	22.4	21.
38	0°58′ N.	139°56′ W.	June 11, 1952	0243–0314	1,279.3	25.1	20.
39	0°04′ S.	139°54′ W.	do.	1131–1210	2,463.1	21.5	28.
40	1°06′ S.	139°51′ W.	do.	2123–2151	1,811.1	[5] 106.7	85.
41	2°08′ S.	139°50′ W.	June 12, 1952	0606–0637	1,727.0	43.8	44.
42	3°13′ S.	139°49′ W.	do.	1313–1344	1,706.5	21.6	27.
43	4°05′ S.	139°49′ W.	do.	2133–2203	1,879.2	45.9	36.
44	5°32′ S.	139°54′ W.	June 13, 1952	0918–0946	1,379.6	29.6	37.
45	7°00′ S.	140°00′ W.	do.	2156–2226	1,399.6	32.2	25.
46	5°29′ S.	140°05′ W.	June 14, 1952	1541–1611	1,142.1	20.6	23.
47	3°43′ S.	140°04′ W.	June 15, 1952	0725–0756	1,729.4	23.0	25.
48	3°00′ S.	140°00′ W.	do.	1444–1514	1,723.2	18.7	22.
49	2°00′ S.	139°53′ W.	June 16, 1952	0019–0049	1,856.6	68.0	51.
50	0°57′ S.	139°45′ W.	do.	0937–1007	1,577.7	57.4	72.
51	0°01′ S.	139°43′ W.	do.	1621–1653	1,703.4	28.2	31.
52	1°00′ N.	139°51′ W.	June 17, 1952	0116–0148	1,383.2	69.8	54.
53	2°06′ N.	140°02′ W.	do.	1051–1120	1,240.3	36.5	47.
54	3°11′ N.	140°13′ W.	do.	1924–1954	1,447.7	32.0	28.
55	4°00′ N.	140°09′ W.	June 18, 1952	0259–0329	1,296.8	28.7	24
56	5°00′ N.	140°04′ W.	do.	1023–1054	1,699.0	23.7	30.
57	5°54′ N.	140°00′ W.	do.	1748–1823	1,903.3	42.0	42.
58	6°47′ N.	139°56′ W.	June 19, 1952	0351–0421	1,514.0	59.1	51
59	8°00′ N.	139°52′ W.	do.	1419–1449	1,532.0	41.8	51
60	9°00′ N.	140°00′ W.	do.	2244–2315	1,515.5	[6] 80.4	61.
Special hauls with 56XXX grit gauze nets:							
45	7°00′ S.	140°00′ W.	June 13, 1952	2231–2302	1,374.2	50.7	
52	1°00′ N.	139°51′ W.	June 17, 1952	0156–0228	1,441.8	122.1	
60	9°00′ N.	140°00′ W.	June 19, 1952	2323–2354	1,202.7	90.9	

[1] Apparent solar time.
[2] Adjusted for day-night difference by the sine transformation method.
[3] Estimated 50 percent euphausiids.
[4] Estimated 30 percent euphausiids.
[5] Estimated 50 percent amphipods.
[6] Estimated 30 percent salps.

TABLE 10.—*Zooplankton volumes obtained on cruise 16 of the* Hugh M. Smith, *with collection data*

Station No.	Position		Date	Time [1]	Water strained, m.[3]	Zooplankton, cc./1000 m.[3]	
	Latitude	Longitude				Sample volume	Adjusted volume [2]
Oblique tows, 200 m. depth; 1-meter nets, 30XXX grit gauze:							
31	3°12′ S	149°28′ W	Aug. 5, 1952	1236–1309	1356.7	15.8	20.9
32	3°12′ S	149°33′ W	Aug. 6, 1952	0040–0119	1430.3	21.1	16.0
33	3°06′ S	149°40′ W	do	1233–1305	1241.7	20.7	27.5
34	3°04′ S	149°42′ W	Aug. 7, 1952	0103–0134	1236.8	33.0	25.2
36	2°57′ S	149°58′ W	Aug. 8, 1952	0030–0100	1683.2	26.6	20.0
37	0°06′ N	149°33′ W	Aug. 10, 1952	0042–0117	1355.6	38.9	29.4
38	0°22′ N	149°36′ W	Aug. 11, 1952	0035–0108	1239.9	31.6	23.9
39	0°59′ N	149°43′ W	Aug. 13, 1952	0037–0109	1702.6	37.5	28.4
41	1°41′ N	149°59′ W	Aug. 15, 1952	0028–0101	1355.4	37.3	28.1
42	1°58′ N	150°15′ W	Aug. 16, 1952	0027–0059	1669.2	42.2	31.8
43	2°15′ N	150°35′ W	Aug. 17, 1952	0038–0110	1513.9	[3] 58.6	44.4
44	2°29′ N	150°47′ W	Aug. 18, 1952	0027–0057	1498.6	50.8	38.3
45	2°39′ N	151°17′ W	Aug. 19, 1952	0025–0058	1862.5	37.2	28.0
46	2°47′ N	151°38′ W	Aug. 20, 1952	0028–0101	2033.3	45.4	34.2

[1] Apparent solar time.
[2] Adjusted for day-night difference by the sine transformation method using a pooled regression coefficient (b=0.1248).
[3] Estimated 30–40 percent siphonophores.

TABLE 11.—*Zooplankton volumes obtained on cruise 18 of the* Hugh M. Smith, *with collection data*

Station No.	Position		Date	Time [1]	Water strained, m.[3]	Zooplankton, cc./1000 m.[3]	
	Latitude	Longitude				Sample volume	Adjusted volume [2]
Oblique tows, 200 m. depth; 1-meter nets, 30XXX grit gauze:							
2	9°00′ N	120°50′ W	Oct. 19, 1952	0024–0050	1529.2	[3] 9.7	7.3
4	7°06′ N	120°00′ W	Oct. 21, 1952	0215–0245	1237.5	48.3	38.7
5	5°50′ N	120°16′ W	Oct. 22, 1952	0231–0304	[4] 2489.5	54.1	43.3
6	4°53′ N	119°59′ W	do	2341–0010	1454.8	54.0	40.5
7	4°01′ N	120°06′ W	Oct. 24, 1952	0016–0048	1532.4	39.3	29.6
8	3°03′ N	120°05′ W	Oct. 25, 1952	0020–0051	1543.8	36.3	27.3
9	1°55′ N	120°14′ W	Oct. 26, 1952	0120–0200	3048.7	32.9	25.4
10	1°02′ N	120°17′ W	Oct. 27, 1952	0126–0154	1458.5	61.8	47.6
11	0°39′ N	120°14′ W	Oct. 28, 1952	0130–0200	[4] 1465.7	69.3	53.5
13	1°04′ S	120°07′ W	do	2326–2356	1617.5	55.9	42.0
15	3°06′ S	120°10′ W	Oct. 29, 1952	2325–2356	1363.8	42.7	32.1
17	4°50′ S	120°21′ W	Oct. 31, 1952	0021–0100	766.0	48.0	36.1
19	6°37′ S	120°24′ W	do	2321–2352	1367.3	37.7	28.3
21	8°40′ S	120°35′ W	Nov. 1, 1952	2322–2355	884.5	38.3	28.8
24	4°12′ S	130°14′ W	Nov. 5, 1952	2246–2316	874.1	43.5	32.9
26	2°15′ S	130°11′ W	Nov. 6, 1952	2245–2319	1121.3	54.0	40.8
28	0°27′ S	130°09′ W	Nov. 7, 1952	2245–2319	1307.0	34.4	26.1
30	1°10′ N	130°08′ W	Nov. 9, 1952	0038–0125	[4] 1812.0	21.9	16.6
31	1°42′ N	130°22′ W	do	2304–2338	1306.8	41.7	31.4
32	3°15′ N	130°14′ W	Nov. 10, 1952	2340–0009	1398.2	56.4	42.3
33	4°08′ N	130°07′ W	Nov. 11, 1952	2351–0020	714.3	64.5	48.4
34	5°42′ N	130°50′ W	Nov. 12, 1952	2241–2316	[4] 1622.5	55.8	42.3
36	7°35′ N	131°14′ W	Nov. 13, 1952	2333–0006	1180.4	30.2	22.9
37	9°00′ N	131°46′ W	Nov. 15, 1952	0032–0105	596.7	57.1	43.0

[1] Apparent solar time.
[2] Adjusted for day-night difference by the sine transformation method using a pooled regression coefficient (b=0.1248).
[3] Doubtful volume; most likely the net was not properly washed down.
[4] Based on estimated meter readings.

TABLE 12.—*Zooplankton volumes obtained on cruise 19 of the* Hugh M. Smith, *with collection data*

Station No.	Position		Direction from island	Hauling course	Distance (naut. miles)		Date	Time [1]	Water strained m.[3]	Zooplankton, cc./1000m.[3]	
	N. lat.	W. long.			From outer reef	From 10-fathom line				Sample volume	Adjusted volume [2]
Oblique tows, 200 m. depth: 1-meter nets, 30XXX grit gauze:											
2	5°52.6′	162°11.1′	W	120°	4.3	0.8	Jan. 14, 1953	0007–0040	1,592.5	17.6	13.2
3	5°52.6′	162°11.6′	W	120°	4.8	1.3	do	0111–0154	[3] 2,105.8	24.7	19.0
4	5°52.6′	162°12.3′	W	120°	5.5	2.0	do	0240–0319	2,053.0	36.5	29.8
5	5°52.6′	162°14.7′	W	120°	7.9	4.4	do	0400–0438	1,514.0	23.3	20.0
6	5°51.7′	162°05.0′	S	105°	0.4	0.3	do	2043–2115	1,054.0	31.9	26.1
7	5°51.0′	162°05.5′	S	105°	1.1	1.0	do	2143–2219	1,384.5	26.1	20.4
8	5°47.6′	162°06.2′	S	105°	4.5	4.2	do	2300–2327	1,073.5	34.8	26.2
9	5°44.7′	162°06.2′	S	105°	7.4	7.1	Jan. 15, 1953	0000–0035	1,423.5	26.6	20.1
10	5°38.0′	162°05.5′	S	105°	14.1	13.8	do	0119–0157	1,551.5	20.2	15.5
13	5°51.4′	162°00.3′	E	80°	1.8	0.6	Jan. 16, 1953	2040–2117	1,136.2	36.1	29.5
14	5°52.0′	161°57.8′	E	80°	4.2	2.4	do	2150–2229	1,299.0	29.4	22.9
15	5°52.8′	161°55.1′	E	80°	6.9	5.1	do	2246–2322	1,178.0	28.2	21.7
16	5°53.0′	161°51.6′	E	80°	10.4	8.6	Jan. 16–17, 1953	2350–0023	1,163.8	34.1	25.6
17	5°55.0′	161°46.0′	E	80°	16.0	14.2	Jan. 17, 1953	0112–0149	1,587.2	21.8	16.7
18 [4]	5°53.2′	162°09.2′	W	140°	2.4		do	1956–2026	1,671.2	54.9	
19	5°55.5′	162°05.5′	N	90°	2.0	1.8	do	2121–2155	1,215.0	45.0	36.0
20	5°54.3′	162°05.5′	N	85°	0.8	0.6	do	2228–2256	1,220.5	30.4	23.2
21	5°56.5′	162°05.5′	N	90°	3.0	2.8	Jan. 17–18, 1953	2335–0004	1,180.8	38.1	28.0
22	5°59.0′	162°05.0′	N	85°	5.5	5.3	Jan. 18, 1953	0036–0104	1,145.0	26.0	19.6
23	6°04.0′	162°05.0′	N	85°	10.5	10.3	do	0153–0221	971.0	33.4	26.1

[1] Apparent solar time.
[2] Adjusted for day-night difference by the sine transformation method using a pooled regression coefficient (b=0.1248).
[3] Based on an estimated flow-meter reading.
[4] This station was located on a shoal with depth of water about 10 fathoms; the haul was made between the surface and about 5 fathoms.

TABLE 13.—*Zooplankton volumes obtained on cruise 15 of the* Charles H. Gilbert, *with collection data*

Station No.	Position		Date	Time [1]	Water strained, m.[3]	Zooplankton, cc./1000 m.[3]	
	Latitude	Longitude				Sample volume	Adjusted volume [2]
Oblique tows, 200 m. depth; 1-meter nets, 30XXX grit gauze:							
2	31°56′ N	119°48′ W	Feb. 19, 1954	1908–1949	2586.6	58.3	52.8
4	29°38′ N	119°50′ W	Feb. 20, 1954	1900–1928	1132.8	54.9	49.8
6	27°40′ N	120°10′ W	Feb. 21, 1954	1852–1918	863.5	[3] 17.8	16.2
8	25°49′ N	120°02′ W	Feb. 22, 1954	1856–1921	1053.5	33.0	30.0
10	23°48′ N	119°30′ W	Feb. 23, 1954	1857–1929	1086.5	16.9	15.3
12	21°36′ N	120°08′ W	Feb. 24, 1954	(4)			
14	19°53′ N	119°10′ W	Feb. 25, 1954	1900–1925	1166.5	13.2	12.0
16	8°54′ N	110°10′ W	Mar. 3, 1954	1847–1921	2112.2	[5] 125.1	116.2
19	5°05′ N	110°16′ W	Mar. 5, 1954	1935–2006	853.8	53.6	46.2
21	3°43′ N	110°34′ W	Mar. 6, 1954	1902–1924	564.0	82.4	74.7
23	2°08′ N	110°03′ W	Mar. 7, 1954	1916–1946	1261.2	64.7	57.3
25	0°32′ N	110°55′ W	Mar. 8, 1954	1904–1940	2619.1	[6] 172.5	156.2
27	1°37′ S	111°28′ W	Mar. 9, 1954	(7)			
29	3°55′ S	112°17′ W	Mar. 10, 1954	1901–1938	1096.5	47.4	42.9
31	5°35′ S	113°52′ W	Mar. 11, 1954	1854–1923	546.1	57.7	53.6
33	7°29′ S	114°49′ W	Mar. 12, 1954	1856–1927	1725.5	21.6	19.5
35	8°42′ S	115°39′ W	Mar. 13, 1954	1902–1932	1448.8	23.7	21.3
37	8°58′ S	121°28′ W	Mar. 15, 1954	1903–1937	1537.6	23.6	21.4
39	8°53′ S	132°07′ W	Mar. 18, 1954	1857–1924	1203.2	14.8	13.4
55	6°25′ S	155°04′ W	Apr. 9, 1954	1926–1957	1250.5	17.7	15.7
57	5°04′ S	155°08′ W	Apr. 10, 1954	1910–1942	1398.4	19.6	17.3
59	3°25′ S	155°20′ W	Apr. 11, 1954	1916–1949	1428.5	16.5	14.6
61	2°17′ S	155°10′ W	Apr. 12, 1954	1917–1946	1255.7	20.9	18.9
63	0°42′ S	154°50′ W	Apr. 13, 1954	1917–1948	1292.2	54.6	48.3
65	1°14′ N	154°58′ W	Apr. 14, 1954	1916–1949	2075.8	33.6	29.7
67	2°23′ N	155°26′ W	Apr. 15, 1954	1909–1948	2257.4	33.4	30.3
69	2°09′ N	157°05′ W	Apr. 16, 1954	1904–1933	1999.3	34.5	31.3
72	3°16′ N	155°13′ W	Apr. 20, 1954	1917–1947	1348.5	[8] 83.4	73.8
74	5°00′ N	154°41′ W	Apr. 21, 1954	1916–1948	1375.2	52.1	46.1
76	6°42′ N	154°47′ W	Apr. 22, 1954	1913–1944	1682.0	31.2	28.3

[1] Apparent solar time.
[2] Adjusted for day-night difference by the sine transformation method using a pooled regression coefficient (b=0.1248).
[3] Small hole (¼″) in bag of net at end of haul.
[4] Sample not quantitative.
[5] Principally euphausiids.
[6] Plus about 12 qts. of salps discarded.
[7] No sample.
[8] Estimated 60 percent salps.

TABLE 14.—*Zooplankton volumes, cc./1000m.³, adjusted for hour of hauling, for* Hugh M. Smith *cruises 2, 5, 7 and 8*

[For unadjusted volumes together with station position, date, time of hauling and description of method, refer to King and Demond (1953)]

Station No.	Cruise 2	Cruise 5	Cruise 7	Cruise 8	Station	Cruise 8
	10.4	13.9	32.0	12.9	53	24.9
		23.0	97.5	14.0	54	25.2
	17.8	14.2	37.7		55	16.7
		22.8	16.2	30.3	56	26.9
		19.1	25.0		57	27.6
		48.2	39.9	22.5	62	19.1
	9.4	23.7	24.8	10.9	63	25.9
		19.0	47.2	11.1	64	21.0
	9.9	14.9	36.3	18.5	65	13.7
		8.4	35.6	23.5	66	25.5
	8.3	32.1	32.7	15.9	67	31.1
		31.3	18.7	46.2	68	40.8
	18.6	27.0	13.5	24.4	69	36.1
		17.9	20.6	12.4	70	24.4
	37.8	25.4	77.1	16.3	71	29.2
		28.6	64.0	19.9	72	23.5
	41.2	25.6	43.5	16.9	73	24.1
		41.5	75.3	24.1	74	17.5
	56.5	33.0	87.5	28.8	75	24.4
		37.3	25.8	67.9	76	12.8
	65.3	57.7	54.6	40.1	77	14.1
		49.3	17.9	29.0	78	16.2
	42.9	86.5	17.7	22.3	79	16.9
		46.9	20.0	47.4	80	15.3
	26.7	54.2		29.2	81	21.4
		28.2		11.6	82	14.1
		27.0			83	18.4
		8.4			84	11.1
		29.4			85	18.3
	42.9	41.5			86	13.3
		24.4			87	27.7
	28.5	29.0		18.5	88	44.3
		73.0		44.8	89	44.9
	73.1	35.3		27.5	90	38.5
		76.7		25.1	91	51.9
	92.5	57.3		48.0	92	37.8
		79.8		31.5	93	27.6
	75.9	71.8			94	33.7
		36.6			95	21.6
	11.6	29.2			96	11.4
		25.6			97	13.3
	8.8	42.8		14.1	98	9.7
		24.2		17.7	99	11.2
	46.6	27.9		15.0	100	13.2
		26.4		18.2	101	13.9
	10.8	17.3		21.3	102	9.9
		22.0		14.9	103	12.2
	3.7	20.6			104	23.2
		22.2			105	10.7
	2.9	42.7			106	13.2
		23.6				
	13.6			31.2		

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OBSERVATIONS ON SEA BIRDS IN THE TROPICAL PACIFIC

By JOSEPH E. KING and ROBERT L. PYLE

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By JOSEPH E. KING and ROBERT L. PYLE

The Pacific Oceanic Fishery Investigations (POFI) of the United States Fish and Wildlife Service, with headquarters in Honolulu, is engaged in a program of oceanographic and fisheries research in the central Pacific. In the period from September 23 to December 17, 1955, the POFI vessel *Hugh M. Smith* made an 86-day, 13,800-mile cruise which afforded the authors an unusual opportunity to observe the sea birds in the equatorial region of the eastern and central Pacific, an area which is not frequently visited by ornithologists.

This cruise of the *Smith,* forming a part of the "Eastropic" expedition in which several research agencies collaborated, followed the route shown in figure 1. The primary objective of the cruise was to obtain information on east-west gradients in water temperature, salinity, chemical nutrients, and abundance of plankton and forage organisms in relation to the current system.

It is standard procedure on POFI cruises for the crewmen standing wheelwatch to record all bird flocks and scattered birds sighted each day. These observations are not usually to the species level, however. In addition to this watch by the crewmen, King maintained throughout the cruise a 1-hour watch each day between 4 and 5 p.m., during which period an effort was made to count and identify to species all birds sighted. On the westbound leg of the cruise, a similar watch was performed each morning, usually at 6 to 7 a.m., by Pyle, who joined the expedition at Manzanillo. The results of these observations, with particular emphasis on the variations in abundance and distribution of the sea birds in respect to the equatorial current system, and an annotated list of the species sighted, are the subject of this report.

In our record keeping we tried to distinguish between scattered birds and birds in flocks. Five or more birds traveling or feeding together as an aggregate were considered a flock. The number of flocks sighted each day and the number (frequently estimated) of individuals in each flock are given in table 1. It is evident from the table that bird flocks varying greatly in number of individuals were observed on less than half the days of the cruise, whereas scattered birds were sighted every day. Because of the small number of bird flocks and their distorting effect on the daily averages, they have been omitted from the detailed analysis in the sections to follow. The average number of scattered birds seen per hour for each day (table 1, fig. 1) was obtained by combining the number sighted by the wheelwatch in 9 to 12 hours of observation with the number sighted by Pyle in one hour and the number sighted by King in one hour, then dividing by the total hours put in each day. We recognize that the "average number" calculated in this manner is hardly an ideal statistic, but it does provide an index to the day-to-day variation in bird abundance and it seemed to be the best way to combine and utilize the available data. All observations made within one day's running (approximately 200 miles) of the Mexican coast or of the different island groups were omitted from the calculations although the species were recorded. Close to land the numbers of birds increased so markedly that an accurate count was impossible.

The identifications are based almost entirely on careful sight records, although representatives of several species came aboard the vessel and were examined in the hand. These included: Wedge-tailed Shearwater, Christmas Shearwater, Black-vented Shearwater, Tahiti Petrel, Hawaiian Petrel, White-throated Storm-petrel, Madeiran Storm-petrel, Leach Storm-petrel, and Sooty Tern. The crewmen were all skilled fishermen who were well acquainted with the common species and possessed remarkable ability to sight birds at considerable distances. There was doubtless some individual variation in the

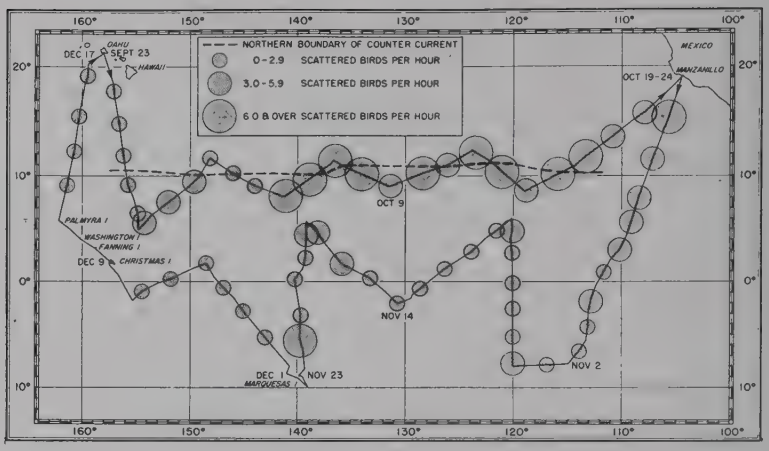

Fig. 1. Track of the M/V *Hugh M. Smith* on the "Eastropic" cruise showing variations in number of scattered birds seen per hour for each day of observation. Sightings by King, Pyle, and the wheelwatch were combined and the resulting average figures grouped into three classes: 0 to 2.9, 3.0 to 5.9, and 6.0 birds and over. The value for each day is plotted at the noon position. All observations within one day's run (about 200 miles) of land were omitted.

Table 1

Average Numbers of Scattered Birds and Birds in Flocks Sighted Each Day of the "Eastropic" Cruise of the *Hugh H. Smith,* Omitting All Observations within One Day's Run (about 200 Miles) of Land

Date 1955	Noon position Latitude	Longitude	Scattered birds: Morning watch, 1 hr.[1]	Afternoon watch, 1 hr.[2]	Wheel-watch, av. No./hr.[3]	Total, av. No./hr.[4]	Birds in flocks: No. of flocks/day[4]	No. of birds in flocks
9/24	17°49′N	157°09′W	....	....	1.0	1.0	0	....
9/25	15°56′N	156°37′W	....	7	1.0	1.5	0	....
9/26	11°56′N	156°12′W	....	....	2.4	2.4	6	309
9/27	09°10′N	155°47′W	....	1	1.5	1.5	0	....
9/28	06°33′N	154°48′W	....	....	1.8	1.8	0	....
9/29	05°31′N	154°13′W	....	10	2.8	3.4	1	25
9/30	07°28′N	151°58′W	....	11	3.5	4.1	5	206
10/1	09°24′N	149°34′W	....	11	4.8	5.4	0	....
10/2	11°38′N	148°04′W	....	5	0.8	1.2	0	....
10/3	10°15′N	145°57′W	....	5	1.0	1.4	0	....
10/4	09°04′N	143°49′W	....	5	2.1	2.4	0	....
10/5	08°00′N	141°10′W	....	4	6.7	6.4	0	....
10/6	09°43′N	138°51′W	....	29	6.3	8.4	3	80
10/7	11°14′N	136°30′W	....	12	5.9	6.5	0	....
10/8	10°09′N	133°59′W	....	15	6.3	7.1	3	175
10/9	09°01′N	131°21′W	....	18	2.3	3.7	2	62
10/10	10°12′N	128°13′W	....	6	7.8	7.4	2	50
10/11	11°00′N	126°02′W	....	9	3.4	3.9	1	50
10/12	12°08′N	123°34′W	....	9	7.7	7.7	1	30
10/13	10°18′N	121°04′W	....	12	7.1	7.5	2	65
10/14	08°36′N	118°50′W	....	6	3.9	4.1	0	....
10/15	10°05′N	115°51′W	....	14	6.9	7.5	1	30
10/16	11°40′N	113°25′W	....	19	10.0	10.5	1	8
10/17	13°36′N	110°51′W	....	6	3.2	3.4	1	20

Date 1955	Noon position Latitude	Noon position Longitude	Scattered birds: Morning watch, 1 hr.[1]	Scattered birds: Afternoon watch, 1 hr.[2]	Scattered birds: Wheel-watch, av. No./hr.[3]	Total, av. No./hr.[4]	Birds in flocks: No. of flocks/ day[4]	Birds in flocks: No. of birds in flocks
10/18	15°46′N	107°57′W	....	2	4.2	3.0	1	35
10/19–24	Mexico							
10/25	15°16′N	105°44′W	4	33	7.0	8.6	1	150
10/26	11°33′N	107°08′W	8	20	4.1	5.2	3	18
10/27	07°58′N	108°25′W	14	8	6.0	5.9	0	....
10/28	05°41′N	109°06′W	19	4	4.3	5.6	0	....
10/29	03°04′N	110°10′W	4	4	3.3	3.4	1	45
10/30	00°59′N	111°32′W	0	4	1.2	1.4	0	....
10/31	01°40′S	112°52′W	15	0	4.0	4.6	0	....
11/1	04°25′S	112°50′W	....	5	1.6	2.0	0	....
11/2	06°46′S	113°54′W	1	0	1.8	1.6	0	....
11/3	07°53′S	116°50′W	0	4	1.1	1.4	0	....
11/4	07°46′S	120°00′W	7	16	2.9	4.5	2	30
11/5	05°14′S	120°00′W	3	3	1.3	1.6	0	....
11/6	02°38′S	120°01′W	1	1	1.8	1.6	1	25
11/7	00°03′S	119°52′W	1	0	2.1	1.8	0	....
11/8	02°50′N	120°00′W	1	10	1.0	1.8	1	17
11/9	04°43′N	120°08′W	18	10	2.0	4.2	0	....
11/10	04°56′N	121°26′W	0	0	1.3	1.1	0	....
11/11	02°52′N	123°50′W	0	6	1.8	2.0	0	....
11/12	01°11′N	126°23′W	0	0	0.6	0.5	0	....
11/13	00°32′S	128°40′W	4	6	2.1	2.6	1	5
11/14	02°02′S	130°46′W	3	4	1.2	1.6	0	....
11/15	00°14′N	133°12′W	0	0	1.0	0.8	0	....
11/16	01°44′N	135°50′W	4	4	4.9	4.7	0	....
11/17	04°48′N	138°16′W	2	3	3.6	3.4	0	....
11/18	04°26′N	139°09′W	0	8	6.1	5.7	1	50
11/19	02°13′N	139°11′W	0	6	1.2	1.5	0	....
11/20	00°14′N	140°10′W	2	2	0.6	0.8	0	....
11/21	03°02′S	139°44′W	1	0	1.0	0.9	0	....
11/22	05°36′S	139°50′W	1	4	8.4	7.4	1	16
11/23–12/1	Marquesas Islands							
12/2	05°13′S	143°01′W	4	2	1.0	1.3	3	113
12/3	02°40′S	145°04′W	2	3	0.7	1.0	0	....
12/4	00°27′S	146°54′W	2	0	0.3	0.4	0	....
12/5	01°42′N	148°38′W	2	1	0.9	1.0	1	25
12/6	00°17′N	151°45′W	4	1	1.3	1.5	1	80
12/7	00°51′S	154°30′W	2	1	1.2	1.2	0	....
12/8–12	Line Islands							
12/13	09°02′N	161°23′W	1	1	0.5	0.5	0	....
12/14	12°18′N	160°43′W	0	1	0.5	0.5	0	....
12/15	15°38′N	160°13′W	2	0	0.4	0.4	0	....
12/16	19°12′N	159°23′W	1	0	0.1	0.1	0	....

[1] By R. Pyle, usually at 6:00 to 7:00 a.m.
[2] By J. King, usually at 4:00 to 5:00 p.m.
[3] With observations throughout a 9- to 12-hour day.
[4] Includes sightings by the wheel-watch, R. Pyle and J. King.

effort they expended and in their interest in the project, but the watch was rotated each day so that differences among observers probably did not greatly influence the results. The bulk of the time spent on these observations was contributed by the crewmen, and we wish to acknowledge and thank them for their assistance.

The most important sources of error in our records, we believe, are those related to the difficulties of accurately observing and identifying birds from a small vessel on the open sea. Many of the birds do not follow the ship but remain at a distance; they are usually seen in fast flight and rarely resting on the surface; the vessel is always rolling

and pitching to some degree, making it difficult to hold binoculars steady; and individuals of some species that have the habit of following vessels may have been counted more than once. Our observations were made from the upper deck of the vessel where visibility was excellent and a bird in flight could be followed through 360° if desired. Also, weather conditions were generally good throughout the cruise; on only a few days did heavy rain or rough seas interfere to any extent. Our data provide some measure of the variation in bird sightings in relation to sea surface and amount of cloud cover.

The most widely used reference in making identifications was Alexander (1954). In the eastern Pacific the publications of Murphy (1936), Peterson (1941), and Blake (1953) were also helpful.

Previous records, principally on the occurrence and distribution of sea birds in the central Pacific, have been provided by Murphy (1924, 1928, 1929), Jespersen (1932–33), Fleming (1950), and Macdonald and Lawford (1954). The nearest approach to an analysis of the bird populations and their relation to environmental factors is that of Murphy and Ikehara (1955) for the mid-central Pacific. No quantitative studies as comprehensive as those of Jespersen (1930) and Moore (1951) on sea birds of the North Atlantic, have been made in the Pacific, to our knowledge. The present study does not change this situation to any great degree but does provide some information on variations in the numbers of birds as related to the current system and to certain other features of the environment.

DESCRIPTION OF THE ENVIRONMENT

The general pattern of the Pacific equatorial current system has been described by Sverdrup, Johnson, and Fleming (1942:708–712). In brief, the major surface currents of this region are the North and South Equatorial Currents flowing toward the west, and the eastward-flowing Equatorial Countercurrent lying in between. Although the boundaries of the Countercurrent (CC) may vary meridionally with longitude and season, its southern and northern boundaries ordinarily occur near 5°N and 10°N latitude in the eastern central Pacific. The South Equatorial Current (SEC) is therefore on both sides of the Equator while the North Equatorial Current (NEC) is confined entirely to the Northern Hemisphere. The general features outlined here apply principally to the central Pacific and may not hold for the extreme eastern part of the region. A detailed study of the oceanographic data from this area is presently being made by POFI and other research agencies.

The Equator is the site of upwelling resulting from divergence of the surface waters. The newly upwelled water is high in nutrients and provides a favorable environment for the growth of plankton. Convergence and sinking of the surface waters, occurring between about 2°N latitude and the southern boundary of the CC, may tend to concentrate the plankton into a rich pasturage for forage organisms, which in turn serve as food for the larger fishes such as the tunas and also for the sea birds.

Enrichment of the surface water by an entirely different mechanism is thought to occur along the northern boundary of the CC. In the eastern and central Pacific this boundary region is an area of shallow thermocline with high-phosphate water occurring within the photosynthetic zone and within the reach of wind-induced turbulence. To the westward the thermocline deepens, reducing the likelihood of enrichment of the surface layer through this combination of factors.

VARIATIONS

Current system.—For purposes of examining variations in bird abundance as related to the current system, we use the six latitudinal subdivisions of the area established by

King and Hida (MS). These are based on natural features and are defined as follows: (1) the NEC from about 20°N latitude to the northern boundary of the CC; (2) the CC with its boundaries being determined at the time of each crossing from vertical temperature sections; (3) a zone of convergence in the SEC extending from the southern boundary of the CC to 1½°N latitude; (4) a zone of divergence and upwelling in the SEC along the Equator from 1½°N to 1½°S latitude; (5) the SEC from 1½°S to 5°S latitude; and (6) the SEC from 5°S to about 14°S latitude. Since special effort was spent on our cruise to investigate the northern boundary of the CC, we established a seventh subdivision of 2 degrees of latitude extending from 1 degree north of the current boundary to 1 degree south of the boundary. The latitudinal limits of these seven zones are shown in figure 2.

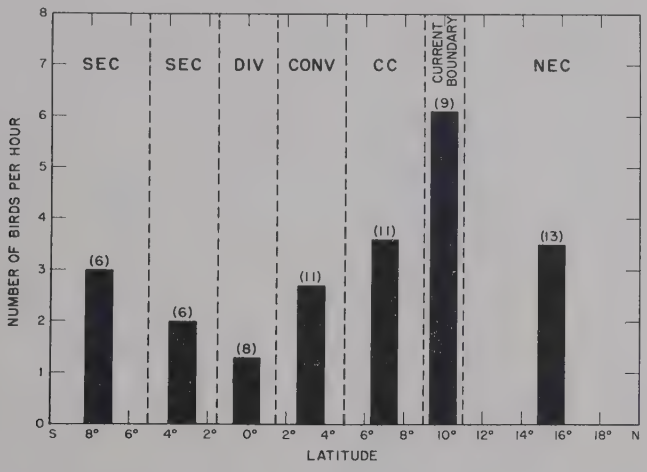

Fig. 2. Variation in numbers of scattered birds sighted per hour of observation in relation to the current system. All sightings within one day's run (about 200 miles) of land were omitted. Number of days on which each average value is based is shown in parentheses.

When the numbers of scattered birds are combined in accordance with these subdivisions of the current system, omitting all sightings within one day's run of land and disregarding differences associated with longitude, we find the largest number of birds occurring along the northern boundary of the Countercurrent and the least number in the zone of divergence on the Equator (fig. 2). It is evident from table 1 that the number of bird flocks was also greater in the region of the Countercurrent than near the Equator; for example on the eastbound leg, 30 bird flocks including a total of about 1145 birds were seen on 25 days (1.2 flocks or 38 birds per day) whereas on the westbound leg south of the CC (south of 5°N) only 13 flocks including about 406 birds were seen on 31 days (0.4 flocks or 13 birds per day). This distribution is generally similar to that described by Murphy and Ikehara (1955, fig. 7) for the central Pacific and also closely parallels the abundance of bigeye tuna (*Parathunnus sibi*) as determined from POFI longline fishing, but is inversely correlated (King and Hida, MS) with the catch of yellowfin tuna (*Neothunnus macropterus*). Reasons for these apparent relationships between birds and subsurface fish are obscure and will not be discussed further in this paper.

In the eastern Pacific (120°W–140°W longitude) the distribution of zooplankton shows a double peak, being high both at the Equator and at the northern boundary of the CC (King and Hida, MS). Of these two "enriched" areas the sea birds, as well as the bigeye tuna, seem to find better foraging conditions at the northern boundary of the CC.

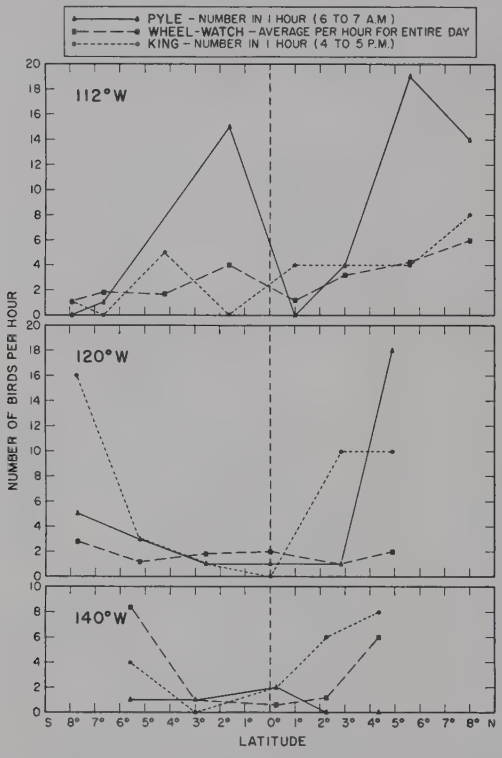
PYLE – NUMBER IN 1 HOUR (6 TO 7 A.M.)
WHEEL-WATCH – AVERAGE PER HOUR FOR ENTIRE DAY
KING – NUMBER IN 1 HOUR (4 TO 5 P.M.)
112°W
120°W
140°W
NUMBER OF BIRDS PER HOUR
LATITUDE
S 8° 7° 6° 5° 4° 3° 2° 1° 0° 1° 2° 3° 4° 5° 6° 7° 8° N

Fig. 3. Variation in numbers of scattered birds comparing the sightings of Pyle, King, and the wheelwatch on three north-south section lines crossing the Equator on longitude 112°, 120°, and 140°W, with the values for each day's observations plotted on the noon position. All sightings within one day's run (about 200 miles) of land were omitted.

Figure 3 shows the latitudinal distribution of scattered birds on the three long station lines crossing the Equator on 112°, 120°, and 140°W longitude. Despite the considerable variation among observers there is evidence of reduced numbers on the Equator and increases to the north and south.

Longitude.—When numbers of scattered birds are combined by 10-degree intervals of longitude, disregarding differences associated with latitude, we obtain a picture (fig. 4) of generally increasing abundance from west to east, with peaks at 140°W and at 110°W longitude. This distribution is probably influenced by the occurrence of the Marquesas

Islands at about 10°S latitude, 140°W longitude and the nearness of the Mexican coast on the east, even though observations within one day's run of land were omitted. The generally low abundance west of 140°W longitude and the increase in numbers along the northern boundary of the CC east of 140°W longitude are clearly shown in figure 1.

There was apparently little variation from east to west in number of bird flocks. The highest average number of flocks (1.1) and the largest average number of birds in flocks (43) sighted per day was recorded for 130°W longitude.

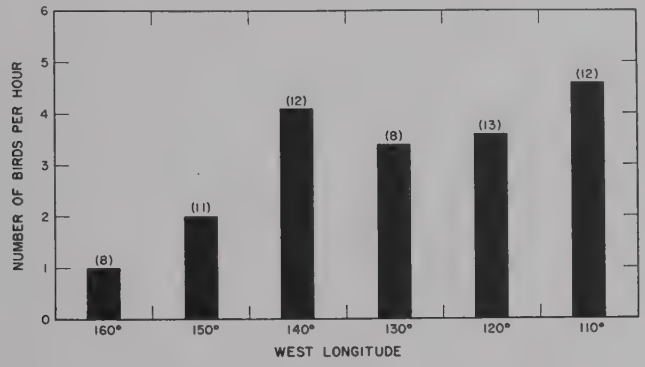

Fig. 4. East-west variation in numbers of scattered birds by 10-degree intervals of longitude. Number of days on which each average value is based is shown in parentheses.

Diurnal.—Our data provide some indication that, during daylight hours, scattered birds were most numerous in the late afternoon period. Numbers of scattered birds sighted by the wheelwatch for each hour from dawn to dusk (6 a.m. to 7 p.m.), and averaged for the entire cruise, but omitting all observations within one day's run of land areas, are shown in figure 5. As the plankton work was conducted each day between 9 and 11 a.m., the bird observations during this period were few and probably not of

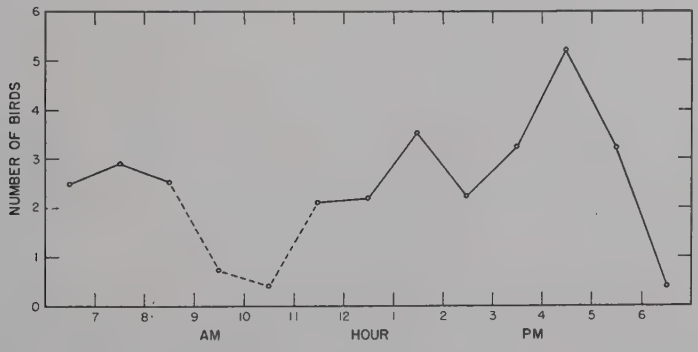

Fig. 5. Variation in number of scattered birds from dawn to dusk as sighted by the wheelwatch. Sightings during 9 and 10 a.m. hours are probably not quantitative. All observations within one day's run (about 200 miles) of land were omitted.

quantitative nature. The peak between 4 and 5 p.m. seems significant although it is partly explained by the presence on the bridge of two observers who were of some assistance to each other in locating birds.

Further evidence of a slightly greater number of scattered birds in flight in the late afternoon, as compared with the early morning, is given by the average sightings of the two special observers on the westbound leg. In the afternoon watch King sighted an average of 4.5 birds per hour whereas in the morning watch Pyle sighted an average of 3.5 per hour. The number of bird flocks varied irregularly with the hour of day, but 36 flocks were sighted between 12 noon and 6 p.m. as compared with 11 flocks between 6 a.m. and 12 noon.

Miscellaneous.—Two factors which may affect the observer's ability to see birds at sea are amount of overcast or cloud cover and the nature of the sea surface. On a clear, calm day bird flocks can be seen with fair regularity at two to three miles with the unaided eye and single birds at one to two miles. With reduction in light through cloudiness and with higher waves and swell to hide low-flying birds it is reasonable to suppose that fewer birds will be seen than under ideal conditions, assuming their actual numbers remain the same.

Although our data are perhaps not sufficient to provide definite conclusions, it would appear from table 2 that increasing cloudiness had no effect on the numbers of scattered birds sighted. Table 3 indicates, on the other hand, that increasing wave height resulted in fewer birds seen. We have no way of knowing, of course, if the true abundance of birds in flight changed with changes in sea surface.

Table 2

Variation in Number of Scattered Birds Sighted in Relation to Amount of Cloud Cover[1]

	Cloud cover, in eighths		
	0–2	3–5	6–8
Average number of birds/hour	5.4	4.3	5.9
Number of hours observed	38	18	46

[1] Based on observations by R. Pyle and J. King during early morning and late afternoon watches.

It is believed that sharp temperature discontinuities or "fronts" occurring in the ocean surface layer may have a concentrating effect on plankton, the basic food in the sea, and consequently influence the distribution of other marine animals. On the westbound leg of our cruise the ship's thermograph (not operating on the eastbound leg of the cruise) recorded 17 fronts with temperature differences across the front ranging from ½° to 4°F. When the positions of these sharp temperature breaks were plotted on a chart similar to figure 1, together with numbers of scattered birds and bird flocks, we could see no evidence of a causal relationship. In only four instances were bird flocks sighted either working over a front or within an hour's run of the temperature discontinuity. We conclude, therefore, that on this cruise the phenomenon had little or no influence on bird distribution or overall bird abundance.

Table 3

Variation in Number of Scattered Birds Sighted in Relation to Sea Surface[1]

	Sea surface, height of waves, in feet			
	< 1	1–3	3–5	5–8
Average number of birds/hour	9.3	6.4	5.0	3.1
Number of hours observed	3	36	55	8

[1] Based on observations by R. Pyle and J. King during early morning and late afternoon watches.

ANNOTATED LIST OF SPECIES

The following species of birds were recorded at sea during the cruise. In many instances records are given by date: the approximate coordinates of these observations may be determined from figure 1 and table 1. Peters (1931, 1934) has been followed in respect to scientific names and order of listing; common names are as given in Alexander (1954).

Puffinus pacificus. Wedge-tailed Shearwater. Recorded on 10 days in the course of the eastbound leg, including a flock of 20 on October 6. Individual birds came aboard the ship on October 4 and 13. A total of eight was seen on October 24 just off Manzanillo, and one was recorded on October 27.

Puffinus griseus. Sooty Shearwater. This completely dark shearwater replaced the very similar Christmas Shearwater in the northeastern portion of the cruise track. It was recorded on October 13, 14, and 15 near 10°N, and again on October 24, 25, and 26, all in the general area southwest of Manzanillo. One bird was seen on November 4 near 7°S, 120°W.

Puffinus nativitatis. Christmas Shearwater. Observed on September 29 and 30 and daily from October 5 to 10 between 141° and 128°W. It was not identified again until November 13 when we had reached 129°W on the west-bound leg. Thereafter it was seen irregularly in the general area north of the Marquesas Islands, including one flock of about 20 recorded on November 18. It became far more abundant near and just north of Christmas Island and was last recorded on December 12 just north of Palmyra Island. On Motu Tabu in Christmas Island lagoon, this species was observed nesting in numbers. Many of the shallow nesting burrows or depressions contained an egg, and several half-grown chicks were seen.

Puffinus opisthomelas. Black-vented Shearwater. First recorded on October 4 when one came aboard the ship. Eight were observed on October 6, and thereafter occasional individuals were seen until October 26, all north of 9°N.

Puffinus assimilis. Dusky Shearwater. Recorded on October 24 and 25, just off Manzanillo, including a flock of about 24 individuals on the 24th, most of which were identified as this form.

Puffinus lherminieri. Audubon Shearwater. Recorded on November 23 and 25 and December 1 in the immediate vicinity of the Marquesas Islands. Several were seen on December 9 within a few miles of Christmas Island.

Pterodroma rostrata. Tahiti Petrel. On November 29 some Marquesan boys brought a bird of this species to the ship while at anchor in Taa Huku Bay, Hiva Oa Island. They stated it had been taken from a burrow on Hiva Oa that same morning. It was identified as this species, rather than *P. alba,* by the large bill, the complete absence of any white flecking on the throat, and by the entirely black outer toe. The bird was photographed and later released. Another bird, probably of this species, but possibly *P. alba,* was seen from the ship on November 30 while still close to Hiva Oa.

Pterodroma alba. Phoenix Petrel. Recorded on September 29 near 6°N, 154°W, and again on December 5 near 1°N, 149°W. The species was abundant on and near Christmas Island, and it was seen frequently in flight over both the lagoon and the land areas of the atoll. On Motu Tabu, Christmas Island, many were observed in and near burrows, and although most nests contained a single egg, no chicks were found. No birds were seen over the ocean out of sight of the atoll, except the two already noted.

Pterodroma phillipii. Kermadec Petrel. Recorded in the course of the eastbound leg on October 5, 7, and 9 near 10°N between 141° and 131°W. Three birds, probably of this species, were seen November 4 near 7°S, 120°W. Distinguished from the Herald Petrel (*P. heraldica*) by the larger body size and the distinct white area toward the tip of the under surface of the wings.

Pterodroma phaeopygia. Hawaiian Petrel. This bird was observed more frequently throughout the cruise than any other species. It was first seen September 27 near 9°N, 155°W and from then until October 30 it was recorded on 24 out of 28 days at sea. Usually about one to three individuals were seen each day, although unusually large counts of nine birds each were noted on October 16, 26, and 28. It was not seen for four consecutive days (October 31 to November 3) at the extreme southeast portion of the cruise track, but scattered birds were seen again on 13 of the next 20 days, in equatorial waters between 120° and 140°W. This included three birds recorded November 22 on 140°W near 6°S. Most of a flock of 25 shearwaters seen on November 6 were thought to have been

this species. Single birds were recorded on 4 of the 8 days between the Marquesas and Christmas Island, and one was seen on December 11 near Washington Island. This species is reported to breed only in Hawaii and the Galapagos Islands (Richardson and Woodside, 1954). However, we failed to record it in the Hawaiian area and it was not seen as we neared the Galapagos Islands.

Pterodroma cookii. Cook Petrel. Small, fast-flying, white-breasted petrels were seen on 19 days in the course of the westbound leg, between Manzanillo and Christmas Island. Fifteen birds were counted on October 25, just off the Mexican coast, but usually there were not more than one or two individuals sighted per day. They were also recorded on four days on the eastbound leg (October 1, 3, 9, and 12). Most of these were thought to be *P. cookii* since the crown appeared gray, concolor with the gray of the upper back, as described by Murphy (1936:720). On the basis of the known range (Murphy, 1929; Jespersen, 1932–33) of these small "gadfly" petrels, many of the examples sighted may have been the Gould Petrel.

Pterodroma leucoptera. Gould Petrel. On the eastbound leg of the cruise this petrel was recorded on September 27 and 30 near 155°W and 151°W, respectively, between 8°N and 9° N.

Bulweria bulwerii. Bulwer Petrel. Fairly abundant around the Marquesas Islands. Many were seen while traveling between islands, but only one was recorded away from the island group; this was seen on November 18 near 4°N, 139°W.

Fregetta grallaria. White-bellied Storm-petrel. Three birds seen on November 3 and single birds observed on November 17 and December 1.

Nesofregetta albigularis. White-throated Storm-petrel. One bird observed on October 6 near 10°N, 138°W. The species was not sighted again until we reached the Marquesas, where single birds were observed on three days. On December 1, one came aboard and was banded and released. One was seen on December 8 as we approached Christmas Island, and several were observed on December 9 over Christmas Island lagoon and also in the ocean nearby.

Oceanodroma castro. Madeiran Storm-petrel. *Oceanodroma leucorhoa.* Leach Storm-petrel. Small, white-rumped petrels were seen east of 144°W almost daily from October 4 to November 20. One bird came aboard the vessel on October 6 and was tentatively identified in the hand as *O. castro.* They were not recorded on November 3, 4, or 5 at the extreme southeast portion of the cruise track, but otherwise during this period we never failed to sight them for more than one day consecutively. From October 31 to November 19, on both sides of the Equator between 113°W and 140°W, a total of 11 storm-petrels came aboard the ship during the evening hours. These birds all belonged to the same species. Seven were captured, banded, and released, and one was preserved as a specimen which was later sent to the United States National Museum and there identified as *O. leucorhoa.* After leaving the Marquesas, storm-petrels were recorded only on December 6, 7, and 8 southeast of Christmas Island, and on December 11 between Christmas and Palmyra. Most of the storm-petrels observed from the vessel during daylight hours appeared to have a broad rectangular rump patch similar to the example of *O. castro* which was examined in the hand. A few were observed to have markedly forked tails.

Oceanodroma melania. Black Storm-petrel. Seen only close to the Mexican coast. One recorded on October 19 and three together on October 24.

Phaëthon aethereus. Red-billed Tropic-bird. Seen on October 19 and 24 close to the Mexican coast.

Phaëthon rubricauda. Red-tailed Tropic-bird. The only species of tropic-bird regularly seen more than 200 miles from land. Infrequently sighted on the eastbound leg to the east of 150°W, but after leaving Manzanillo individuals and pairs were seen frequently from October 26 to November 20, and again from December 4 to 15. Not recorded in or near the Marquesas group. On Motu Tabu, in Christmas Island lagoon, about ten nests were located, each containing an egg or a chick. The chicks were in all stages from very young to nearly full grown.

Some individuals in the open ocean either lacked the long central tail feathers altogether, or had two very small white feathers protruding from the tail. While these individuals did not have the typical mottled pattern of young birds, they sometimes appeared dingy on the back and usually the bill was darker than normal. They were usually seen in the company of a bird in typical adult plumage.

Phaëthon lepturus. White-tailed Tropic-bird. Recorded near the Hawaiian Islands on September 24 and December 15 and 16. Common in and around the Marquesas Islands.

Fregata magnificens. Magnificent Frigate-bird. Common in Manzanillo harbor, and individuals

seen at sea on October 24 and 25 were probably this species. A flight of six birds seen on October 29 was also presumed to be this species.

Fregata minor. Great Frigate-bird. Common in and around Christmas Island.

Fregata ariel. Lesser Frigate-bird. Frigate birds were fairly common in the Marquesas Islands, and every adult male definitely identified belonged to this species.

Pelecanus occidentalis. Brown Pelican. Common in and near Manzanillo.

Sula nebouxii. Blue-footed Booby. Several seen on November 19 just off the Mexican coast, but they were much fewer in number than *S. leucogaster.*

Sula dactylatra. Blue-faced Booby. Four birds recorded on September 28 and 29 between 5°N and 7°N, 139°W. Not definitely identified again until December 8 when we were approaching Christmas Island. Many were seen on and around Christmas Island on December 9, and several were recorded over the ocean between Christmas and Palmyra. One was seen on December 14 near 12°N, 160°W.

Sula sula. Red-footed Booby. Common around the Marquesas Islands, where all individuals sighted were in the brown phase. At Christmas Island, most of the birds had brown wings and back, but were otherwise white. Birds seen between Christmas and Palmyra were in the white phase typical of the Hawaiian Islands.

Sula leucogaster. Brown Booby. Abundant close to the Mexican coast and also around the Marquesas Islands. Several were seen at Christmas Island. None recorded at sea more than 100 miles from land.

Pluvialis dominica. Golden Plover. One observed in flight at sea on September 28.

Arenaria interpres. Ruddy Turnstone. On October 3, near 10°N, 146°W one circled the ship for about 10 minutes. A flock was observed on October 19 near the Mexican coast.

Phalaropus fulicarius. Red Phalarope. Four unidentified phalaropes were recorded on October 19 just off the Mexican coast, and four more were observed in the same general area on October 24. Again, four were seen on November 8, near 4°N, 120°W in association with a marked convergence or "front" in the upper layer of the ocean. On the following morning, still in the convergence zone, an individual phalarope was observed very close to the ship and identified as this species.

Catharacta skua. Great Skua. A bird identified as this species passed close by the ship on November 13, near 1°S, 129°W.

Stercorarius pomarinus. Pomarine Jaeger. Jaegers probably of this species were recorded occasionally on all portions of the cruise track, between September 29 and December 6.

Larus sp. One gull, possibly *L. californicus* in second-year plumage, followed the ship briefly on October 13, more than 1000 miles from the Mexican coast.

Sterna sp. Two or three large flocks of medium-sized white terns with light gray mantles were observed together on October 24, about 50 miles off the Mexican coast.

Sterna fuscata. Sooty Tern. Observed far more frequently than any other tern. Recorded on only four days on the eastbound leg, but abundant close to the Mexican coast. Between Manzanillo and the Marquesas it was seen occasionally, including a flock of 25 to 30 birds on November 4 and a flock of 14 birds on November 8 in association with a convergence front in the upper layers of the ocean. The species was abundant in and around the Marquesas and was observed daily at sea between the Marquesas and Palmyra Island. It was not seen after December 11.

Thalasseus bergii. Crested Tern. Nine individuals recorded on Christmas Island, on the same sand bar at the lagoon entrance where King (1955) found them in 1953.

Procelsterna cerulea. Blue-gray Noddy. Common in and near the Marquesas and Christmas Island. On Motu Tabu in Christmas Island lagoon several eggs were found.

Anoüs stolidus. Common Noddy. Several birds of this species were seen in the Marquesas Islands and on Christmas Island. In addition, two birds were recorded at sea on October 10 near 10°N, 128°W.

Anoüs minutus. White-capped Noddy. Common in and near the Marquesas and Christmas Island. On Motu Tabu in Christmas Island lagoon nesting was nearly completed and only a few nearly full grown young were seen.

Gygis alba. White Tern. Abundant in and around the Marquesas Islands. Although many were observed on Nukuhiva Island, none was captured or collected so that the form *G. a. microrhyncha* was not definitely identified. This species was also abundant on Christmas Island, where on Decem-

ber 9 nesting was in progress and all stages from eggs to nearly grown chicks were seen. Recorded at sea each day between Christmas and Palmyra islands.

Unidentified Ducks. A flock of about 12 ducks flying south was recorded on October 5. Individual ducks were observed on October 6, 9, 10, and 27. None was close enough to identify the species.

SUMMARY AND CONCLUSIONS

Forty species of sea birds, principally shearwaters, petrels, storm-petrels, tropicbirds, frigate-birds, boobies, and terns, were sighted on the "Eastropic" cruise of the M/V *Hugh M. Smith* to the central and eastern tropical Pacific.

Scattered sea birds were most abundant along the northern boundary of the Countercurrent at about 10°N latitude. The largest numbers occurred near 110°W longitude, influenced no doubt by the nearness of the Mexican coast; and on 140°W longitude a second area of high abundance was found which may be related to the shallow thermocline, high phosphate concentrations, and rich zooplankton conditions characteristic of this region.

There is some indication that in the daylight hours scattered birds were most numerous during the late afternoon period. Increasing cloudiness had no effect on the numbers of birds sighted; but when the wave height increased, fewer birds were recorded.

There was little or no evidence that birds occurred in greater frequency in areas of marked temperature change in the sea surface.

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